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Robust Decision-Making in the Water Sector

A Strategy for Implementing Lima's Long-Term Water Resources Master Plan

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Abstract

How can water resource agencies make smart investments to ensure long-term water reliability when the future is fraught with deep climate and economic uncertainty? This study helped SEDAPAL, the water utility serving Lima, Peru, answer this question by drawing on state of the art methods for decision making under deep uncertainty. These methods provide techniques for evaluating the performance of a water system over a wide range of plausible futures and then developing strategies that are robust across these futures. Rather than weighting futures probabilistically to define an optimal strategy, these methodologies identify the vulnerabilities of a system and then evaluate the key trade-offs among different adaptive strategies. Through extensive iteration and collaboration with SEDAPAL, the study used these methods to define an investment strategy that is robust, ensuring water reliability across as wide a range of future conditions as possible while also being economically efficient. First, on completion, the study helped SEDAPAL realize that not all projects included in the Master Plan were necessary to achieve water reliability, and the utility could save 25 percent (more than $600 million) in investment costs. Second, the study helped focus future efforts on demand-side management, pricing, and soft infrastructure, a refocusing that is difficult to achieve in traditional utility companies. Third, the study helped SEDAPAL gain the support of regulatory and budget agencies through the careful analysis of alternatives. Fourth, the study allowed the utility to postpone lower priority investments, and to analyze future options based on climate and demand information that simply is not available now.

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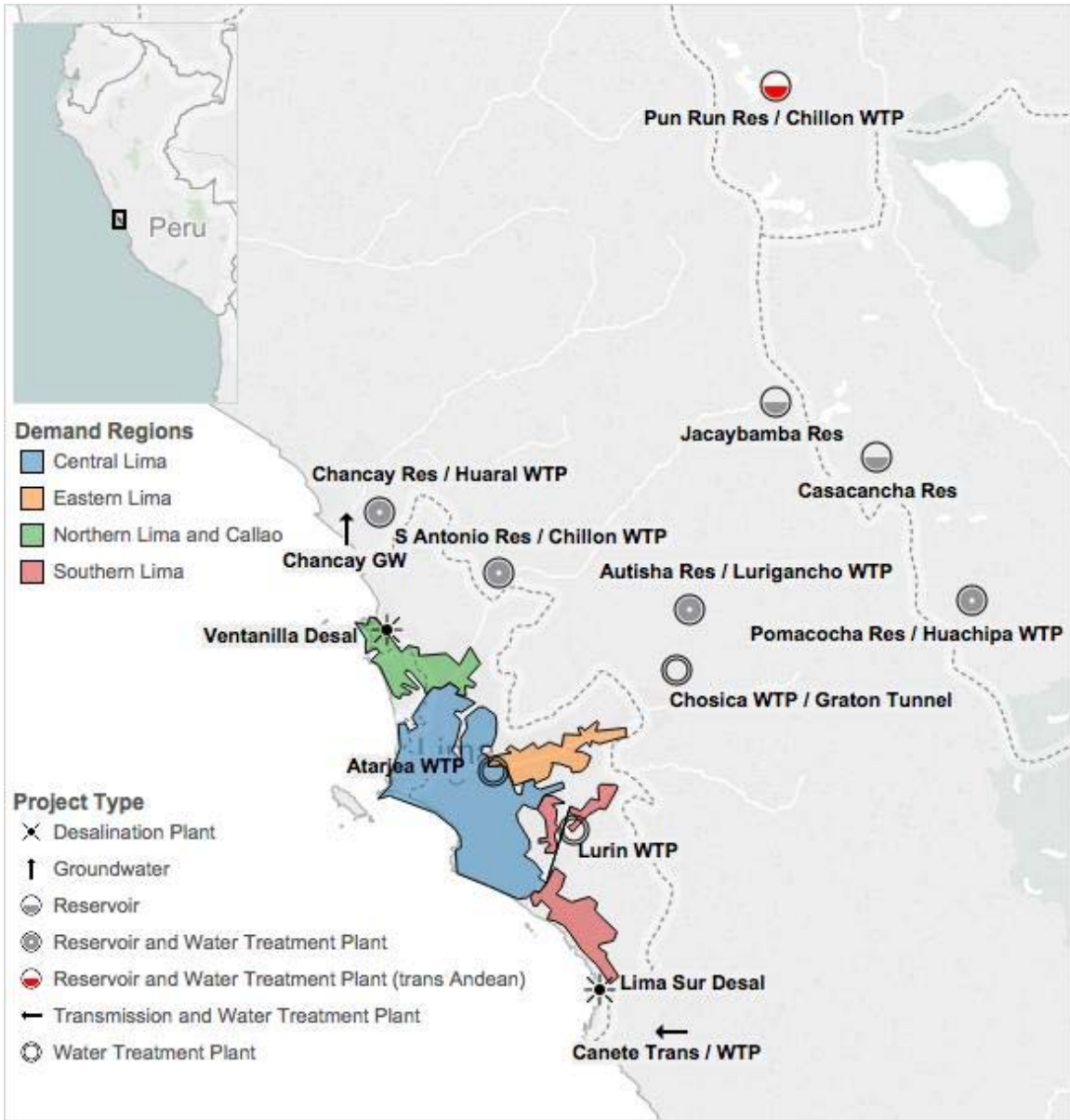4. SEDAPAL

Acknowledgments

1 Introduction

Lima, the capital of Peru, faces major water-related challenges. Home to approximately 9.8 million people (INEI, 2013), it is the fifth largest metropolitan area in Latin America. With average precipitation of just 6 mm per year (WMO, 2015), it is also the second largest desert city in the world. A rapidly growing population with approximately one million underserved urban poor, current water shortages, competition for water between sectors, and climate change impacts may leave the region under perpetual water stress.

SEDAPAL, Lima's water utility, provides water to most of the metropolitan region, which includes the adjacent port district of Callao of approximately one million people (INEI, 2013). Nearly all of SEDAPAL's supplies are drawn from the Chillón, Rimac, and Lurin river basins in the region. Recognizing the urgency of Lima's water situation, SEDAPAL has developed an aggressive multi-billion dollar Master Plan, which includes 12 major infrastructural investment projects that SEDAPAL proposes to implement between now and 2040 at a cost of US $2.3billion. SEDAPAL is further considering two additional water supply projects for a cost of US $400 million. As Figure 1-1 shows, these 14 investments are a mix of reservoirs, water treatment plants, desalination plants, and tunnels to transfer water between watersheds. Together, the investments are designed to meet the 30% increase in water demand that SEDAPAL projects for the coming decades. Lima's demand for water is distributed across four regions:

- Central Lima, which has 85% of demand and is in the Rimac basin;
- Northern Lima and Callao, which has 7% of demand and is in the Chillón basin;
- Eastern Lima, which has 6% of the city's demand and is also in the Rimac basin;
- Southern Lima, which has 2% of the city's demand and is in the Lurin basin.

In 2014, SEDAPAL submitted its Master Plan to national regulators for approval. In mid-2015, SEDAPAL obtained the Master Plan's approval including management goals, rate formula, and tariff structures for the regulatory 5-year period 2015-2020.

Figure 1-1: Map of projects in the Master Plan and demand areas in Lima

Consistent with the state of practice at many water utilities, SEDAPAL developed its Master Plan by projecting future demands based on recent socioeconomic trends and by projecting future water supply based on historical climate conditions. Yet future water supply and demand in Lima may differ markedly from that of the past. Rapid growth in recent years, particularly through informal settlements in the outskirts of the city, could continue (Plöger, 2012). This growth could accelerate if migration from rural areas increases (INEI, 2001), or could level off if current socioeconomic pressures change. Simultaneously, climate change may alter the availability of water supplies to Lima. In the past, Lima relied heavily on glacier melt for its water. However, two-thirds of the glaciers feeding the Rimac's headwaters have disappeared, decreasing the river's glacier-contributed volume by 90% in the past 40 years (Vince, 2010). Today, Lima's water supply depends primarily on precipitation in the upper watersheds. Future precipitation

changes are uncertain—rainfall may increase or decrease—but droughts may also become more severe and more common (IPCC, 2014). The combined effects on streamflow in the basins that serve Lima are highly uncertain.

These uncertainties raise important questions for decision makers concerned with water reliability in Lima. Are the capital projects in the Master Plan sufficient to ensure reliability in the face of deeply uncertain future climate change and demand? On the other hand, are all proposed projects necessary to achieving reliability? Many projects are challenging to implement—how should considerations of project feasibility shape the city's investment strategy? Ultimately, how should projects be prioritized? Which should be implemented now, which can be delayed until they are necessary, and what specific indicators would trigger their implementation?
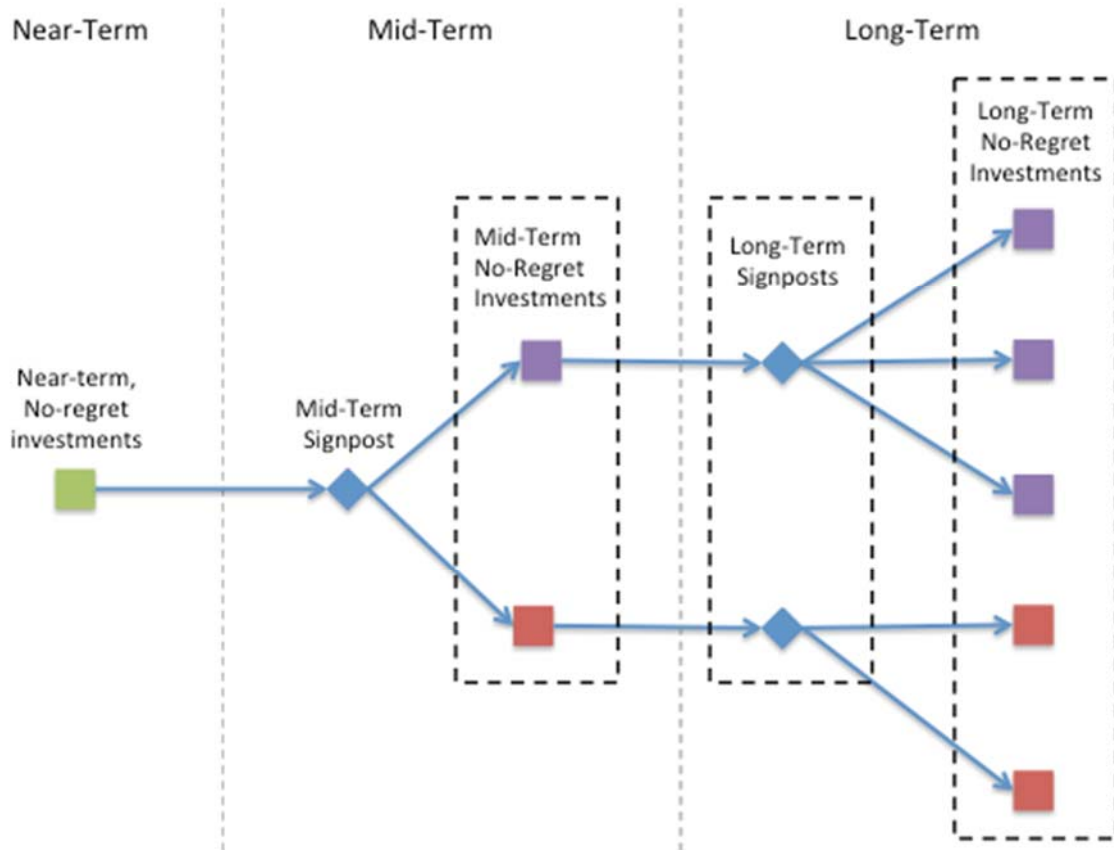
This study draws upon state-of-the-art methods for decision making under deep uncertainty (DMU) to give SEDAPAL and decision makers in Lima answers to these pressing questions. It draws upon several methodologies including Robust Decision Making, Decision Scaling, and Adaptive Pathways, to prioritize the investments in SEDAPAL's Master Plan. Together these methods help define an investment strategy that is *robust*, ensuring water reliability across as wide a range of future conditions as possible while also being economically efficient. This strategy has two key characteristics of a robust plan:

1. It is *no-regret*. It identifies investments and projects that are useful no matter what the future brings;
2. It is *adaptive*. It guides decision makers on how to implement future investments and projects as climate, demand, and other future conditions evolve.

The strategy is defined in a decision tree as shown in Figure 1-2. It consists of a set of near-term, no-regret investments that SEDAPAL can embark upon now; signposts of specific project feasibility, streamflow, and demand conditions SEDAPAL should monitor in the medium and long term; and sets of deferred projects that SEDAPAL should implement if the signposts are triggered. Section 7 describes the strategy and decision tree in detail.

Importantly, the strategy prioritizes among the 14 supply-side investments. Yet efficiency and demand management will play a key role in ensuring water reliability in Lima, particularly as they may be more cost effective than some of the supply-side investments. At the time of this project, SEDAPAL sought to focus its analysis on the Master Plan projects as it concurrently explored ideas for demand side and efficiency options. Therefore, while this analysis does not explicitly evaluate efficiency and demand management actions, it highlights the need for such actions by testing the limits of the water reliability that can be achieved with the proposed projects. In Section 8, we recommend evaluating demand and efficiency actions alongside supply-side investments in a follow-on analysis to develop an integrated water resource management plan.

Figure 1-2: Schematic of a decision tree of investments for SEDAPAL

This project helps SEDAPAL understand its Master Plan more fully. It enables SEDAPAL to assess climate change threats without first needing to predict the future climate. It helps SEDAPAL identify projects that are particularly important for achieving water reliability. And, it reveals the strengths and vulnerabilities of its Master Plan concisely—as a specific set of conditions in which the Master Plan and related projects can achieve water reliability and in which additional actions may be necessary. It also helps SEDAPAL implement its Master Plan robustly by identifying near-term, no-regret projects that it can embark upon now, while pursuing additional actions adaptively as future conditions evolve.

An interactive, analytical decision support tool accompanies this paper. We used this tool for the analysis and at project workshops to help SEDAPAL's staff and managers understand the analysis. Each of the analytical figures in this paper is a screenshot of an interactive component of the decision support tool. The tool is available online at https://goo.gl/BRojPW.

The remainder of this paper describes this analysis. Section 2 presents the methodologies behind the analysis, Section 3 describes how they were used to engage with stakeholders in Lima, and Section 4 presents the key elements of the analysis that emerged from the stakeholder engagement. The analysis and findings are presented in the next three sections. Section 5describes the baseline vulnerability of the current system and of the full Master Plan and related projects. Section 6 shows the portfolios and an

assessment of how they can help SEDAPAL achieve water reliability efficiently. Section 7 presents a robust, adaptive decision tree of no-regret projects based on those results. The final section summarizes key findings, next steps, and future applications. In addition, Appendix A accompanies Section 4, providing details on the demand and streamflow uncertainties.

2 Methodology

Water resource planners are increasingly turning to decision making under uncertainty (DMU) methods to address climate change and other uncertainties in their long-term plans (Brown, 2010; Groves *et al.*, 2008). Central to these approaches is the recognition that it is not possible to determine the likelihoods of plausible future states of the world in order to identify "optimal" water management strategies. The most appropriate set of water management investments may differ significantly depending on what the future holds. Therefore, developing an optimal strategy and then exploring performance sensitivities does not provide the necessary information to determine a prudent course of action. Instead, the goal must be to identify "robust" strategies—those that will perform satisfactorily across the wide range of possible futures (Groves *et al.*, 2014b).

Robust water management strategies generally consist of a portfolio of individual management decisions, such as new infrastructure, operational procedures, or water use efficiency programs. The implementation of the portfolio is not predefined, but rather is adaptive and adjusts in response to new information about future conditions. As there are generally many different ways to achieve water management objectives, evaluating trade-offs among the different options and portfolios is critical to the final decision making and achieving stakeholder support for policies.

2.1 Methods for Robust, Adaptive Water Management

Developing robust, adaptive water management strategies requires new analytic techniques. Water agencies must consider more than just the historical hydrologic record when projecting future hydrologic conditions. For systems that are supply limited, evaluating a range of demand projections is also essential to understanding the full range of possible water management needs. Other factors important to the design and performance of a water management system (for instance, water regulations or investment effectiveness) are also highly uncertain and should be explored.

DMU methods provide techniques for evaluating the performance of a water system over a wide range of plausible futures and then developing strategies that are robust across these futures (Kalra *et al.*, 2014). Rather than weighting futures probabilistically to define an optimal strategy, DMU methods identify the vulnerabilities of an agency or utility's system and then evaluate the key trade-offs among different adaptive strategies. Through iteration, often with extensive and direct participation of decision makers and stakeholders, a robust, adaptive strategy is identified. Such a strategy defines a set of

near-term investments, signposts—conditions that would trigger new actions or adjustments—and deferred actions for possible future implementation.

Early applications of these methods to water planning include Robust Decision Making (Groves and Lempert, 2007; Lempert *et al.*, 2003) (RDM) studies in Southern California (Groves *et al.*, 2008, 2014a; Lempert and Groves, 2010) and the U.K. (Dessai and Hulme, 2007). These applications illustrated techniques for generating and evaluating a large ensemble of futures, identifying the key vulnerabilities of current management through a process called "scenario discovery" (Bryant and Lempert, 2010), and then highlighting key trade-offs among the most robust strategies. The Southern California application also introduced rudimentary adaptivity into the robust strategies based on implementing additional management actions if the gap between water demand and available supply grew too small. Recent other applications include two pilot studies for the Water Resources Foundation (Groves *et al.*, 2014b), an evaluation of the Integrated Resources Plan of the Metropolitan Water District of Southern California (Groves *et al.*, 2014a), an application to flood risk mitigation in Vietnam (Lempert *et al.*, 2013a), and for the U.S. Bureau of Reclamation's Colorado River Basin Study (Bureau of Reclamation, 2012; Groves *et al.*, 2013).

Concurrently, a related methodology has been developed called Adaptation Pathways (Walker *et al.*, 2001), which focuses on defining a comprehensive set of alternative sequences of decisions and identifying the conditions that could guide decision makers along the most appropriate sequence. Haasnoot et al. (2013) demonstrates this approach for flood control in the Netherlands, which includes novel visualizations of different sequences of investments, called "pathways." Another related methodology, called Decision Scaling (Brown *et al.*, 2012), has been described and applied in the Great Lakes region (Brown *et al.*, 2011) and the Niger River Basin (Brown, 2011). Decision Scaling provides techniques for extensively exploring plausible climate conditions to define the key climate-related thresholds that distinguish different robust strategies.

The World Bank is supporting other projects organized around DMU in several developing countries. These projects range from hydropower investments in Nepal and Africa (Cervigni *et al.*, 2015), urban flood management in Sri Lanka, and transport network's vulnerability in Peru and Ecuador. A conceptual framework has also recently been developed by the Water Global Practice to guide project planners through the application of DMU techniques to climate change risk assessment and risk management.

These methods recognize the importance of decision maker and stakeholder involvement in the decision analysis. For example, to help SEDAPAL planners gain a deeper appreciation for "deep uncertainty", the study team facilitated a "serious game" (Mendler de Suarez *et al.*, 2012) called "Decision for the Decade".[1] The study team then developed participatory, interactive decision support tools to evaluate simulation results and develop portfolios of water management investments. The tools developed are similar to those recently used to support the development of Louisiana's 2012 Coastal

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[1]Information on this "serious game" can be found on the web at: http://www.greengrowthknowledge.org/page/decision-making-under-uncertainty-testing-methodologies-real-world

Master Plan (CPRA, 2012; Groves and Sharon, 2013) and the Bureau of Reclamation's Colorado River Basin Study (Bureau of Reclamation, 2012; Groves *et al.*, 2013).

2.2 Methodological Steps in this Study

This study is based on the sequence of analytic steps described in the RDM literature, and it assimilates techniques from the other related DMU methodologies. Specifically, this study is guided by Robust Decision Making, which offers a structured approach to stress testing a water management plan and evaluating trade-offs among alternatives. Consistent with Decision Scaling, it evaluates SEDAPAL's system across a wide-range of hydrologic conditions developed by adjusting historical streamflow by incremental amounts using the Delta Method (Anandhi *et al.*, 2011). The study uses an interactive, analytic decision support approach to define alternative portfolios consistent with different budgets, SEDAPAL's concerns about the feasibility of certain projects, and uncertain future supplies and demands(Groves *et al.*, 2014c). Lastly, it uses concepts from the adaptive planning literature to define a robust and adaptive decision tree for SEDAPAL's investments.

Figure 2-1 shows the basic iterative steps described in the RDM literature and highlights where techniques from other methods are incorporated.

Figure 2-1: DMU steps used to guide study
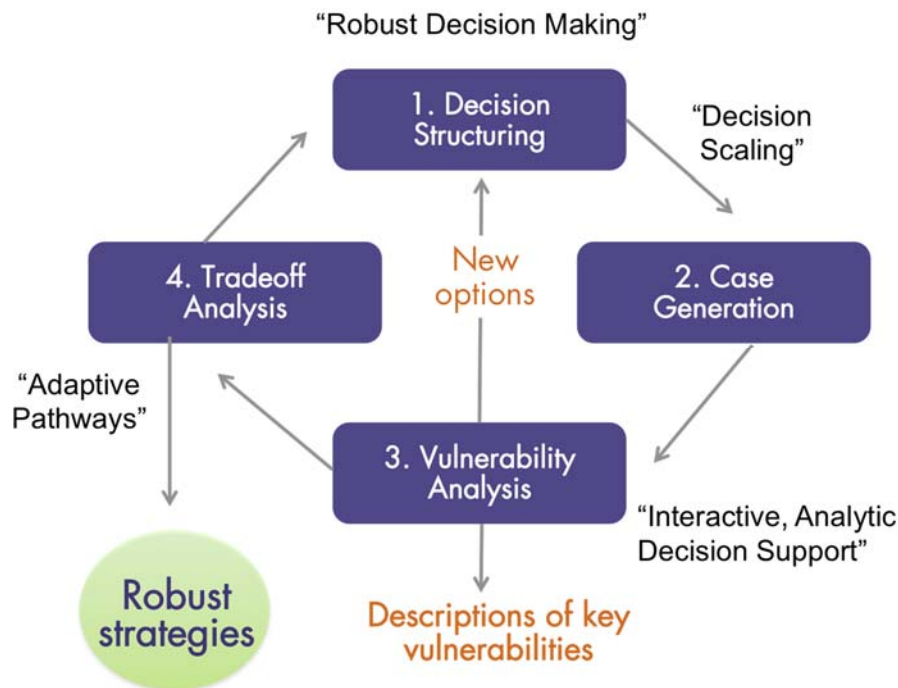
Note: Figure adapted from Lempert et al. (2013b)

The DMU approach used in this study began with a decision structuring exercise (Step 1,Figure 2-1). The study team worked with SEDAPAL planners to identify the key risk factors that might affect the success of the Master Plan, to define the elements of the

Master Plan to evaluate, and to specify the performance metrics that would be used to assess the Plan's robustness. Based on this information, the team developed a water management model to simulate the performance of SEDAPAL's system under different futures and levels of investment. Sections 3 and 4 provide details from this step.

Our analysis first defined the baseline vulnerabilities, described in Section 5. We evaluated the performance of SEDAPAL's current water management system in 2040 across 300 different plausible future scenarios of future supplies and demand using the water management model (Step 2, Figure 2-1). We then assimilated these results into a decision support tool and identified the key vulnerabilities—that is, the key uncertain drivers that would lead SEDAPAL's plan to not achieve its goals (Step 3, Figure 2-1).

We then returned to Step 1 and developed a large set of portfolios of projects--all variations of the SEDAPAL Master Plan. To do this, we evaluated the performance of each individual project across the 300 futures and then used an interactive, analytical decision support tool to define optimal portfolios for each of the 300 futures. By evaluating the vulnerabilities of each portfolio, we honed in on a small set of different portfolios that would achieve SEDAPAL's goals under the wide range of different futures. This portfolio analysis is described in section 6.

Our last analytic step was to develop a single, adaptive strategy for SEDAPAL. By analyzing simulation results of each portfolio, we identified the key ingredients of a robust, adaptive strategy:

- Near-term no-regret projects—project included in all portfolios,
- Signposts—uncertain conditions that should trigger additional SEDAPAL investment,
- Deferred actions—additional investments to implement under different future conditions, and
- Remaining vulnerabilities—conditions in which any implementation sequence of Master Plan projects would not meet SEDAPAL's goals.

This step is described in section 7.

3 Engagement with SEDAPAL and Stakeholders

Following best practices in decision support, this project embedded analytics in an intensive and structured participatory process with SEDAPAL and other stakeholders. It began in December 2013 and the analysis was completed in March 2015, with this final report published in the subsequent months. Figure 3-1 shows activities and milestones.

This project kicked off with a multi-day workshop at SEDAPAL in December 2013 to build a shared understanding of the problem and cultivate relationships between stakeholders and analysts. At the workshop, we collaboratively scoped the analysis (Step 1 in Figure 2-1) and elicited the key analytical elements discussed in Section 4. We launched data gathering needed to build the WEAP model. We also held meetings to keep other stakeholders abreast of the new study, including Peru's National Water

Authority (ANA), the water supply and sanitation regulatory authority (SUNASS), local non-governmental organizations, and municipal authorities. This workshop also identified local members of the technical team from SEDAPAL and the University of Callao. The importance of this workshop cannot be overstated, particularly in analyses involving participants who are geographically dispersed, speak different languages, and bring different skills to the effort.

In April 2014 we held another set of workshops in which we presented preliminary findings from the vulnerability analysis with and without full implementation of SEDAPAL's Master Plan. We met with both SEDAPAL's management and other stakeholders, and we adjusted the scope of the analysis based on their feedback. In October 2014, we again met, this time to develop different implementation portfolios using the interactive, analytic decision support tool. This enabled us to continuously ensure that the analysis answered questions that were most important to SEDAPAL and in a way that was practical for their planning.

At the final workshop in March 2015, we presented the results to SEDAPAL's board of directors, other municipal and national stakeholders, and guests from several Andean countries. The workshop was highly participatory, using modeling results and an interactive planning tool to illustrate both the threats to water reliability and a strategy for prioritizing investments that responds to those threats. It also included a one-day training session with academics on the basics of this methodology.

Finally, while the workshops were key opportunities for in-person engagement, members of SEDAPAL's technical staff were part of the analytical team throughout the project; they brought their expertise on Lima's water needs and SEDAPAL's system and goals. We met weekly—and at times daily—by phone. We attribute the success and value of this project in large part to SEDAPAL's enthusiasm for innovative analysis and their commitment to participating in this analysis.

Figure 3-1: Project Timeline

4 Scope of the Analysis

We organized the key components of the decision-centric analysis using an "XLRM" framework (Lempert *et al.* 2003; Groves et al., 2014b). This framework was the focus of the first workshop and helped to build a common understanding of the water management challenges among the technical team and stakeholders throughout the project. It also usefully guided data gathering and model development.

The letters X, L, R, and M refer to four categories of factors:

- **Policy levers (L)** are actions that decision makers want to consider, in this case the components of SEDAPAL's Master Plan and related investments;
- **Exogenous uncertainties (X)** are factors like climate change and demand that are outside the control of decision makers but that may affect the ability of actions to achieve decision makers' goals;
- **Metrics (M)** are the performance standards used to evaluate whether or not a choice of policy levers achieves decision makers' goals, e.g. water reliability; and
- **Relationships (R)**, generally represented by simulation models, define how the policy levers perform, as measured by the metrics, under the various uncertainties.

The XLRM matrix developed for this study is summarized in Table 4-1. This section continues to describe the policy levers (L) under consideration, the metrics (M) used to judge the effectiveness of those policies, the uncertainties (X), and lastly the models (R) that quantify the relationships among the factors.

Table 4-1: XLRM framework of key factors in this analysis

Uncertainties (X)	Policy Levers (L)
- Future water demand - Future stream flow - Project feasibility	12 projects in SEDAPAL's Master Plan 2 additional projects - Budget for infrastructure (Efficiency and demand management)
Models (R)	**Metrics (M)**
- WEAP Model - Interactive, analytic decision support tool	90th percentile of monthly met demand, as a percent of total demand - Cost of plan

4.1 Policy Levers (L)

SEDAPAL's Master Plan consists of twelve investment projects; a mix of dams, tunnels, water treatment plants, desalination plants, and tunnel transfers. SEDAPAL is also considering two additional investment projects—Cañete transfer/water treatment plant (WTP) and Chancay Reservoir—that were considered important to evaluate but not part of this plan. Table 4-2summarizes the key characteristics of these projects. The first column identifies the shorthand name we use for each project throughout this paper, the second summarizes the key elements of each project, the third notes the amount of water the project is intended to supply, and the fourth is the estimated cost of each project.

Table 4-2: Master Plan and related projects evaluated in this analysis

Project Name	Project Description	Additional Designed Supply By Region and Season	Cost (M USD)
Atarjea WTP	Expansion of Atarjea WTP	2 m^3/s to Central Lima all year round	1.6
Autisha Res / Lurigancho WTP	Autisha Reservoir and S. J. Lurigancho WTP	1.2 m^3/s to Central Lima in the dry season only	21.9
Cañete Trans / WTP*	Water transfer from river Cañete, South of Lima, with a WTP in Lurin	3.5 m^3/s to Southern Lima (70%) and 1.5 m^3/s to Central Lima (30%) all year round	320
Casacancha Res	Casacancha Reservoir	1.8 m^3/s to Central Lima in the dry season only	25
Chancay GW*	Groundwater extraction from the lower watershed of the river Chancay	1.5 m^3/s to Northern Lima and Callao in the dry season only	62
Chancay Res / Huaral WTP	Chancay Reservoir and Huaral WTP	2 m^3/s to Northern Lima and Callao all year round	274
Chosica WTP / Graton Tunnel	Chosica WTP and enlargement of the Graton tunnel	0.6 m^3/s to Central Lima (40%) and 0.9 m^3/s to Eastern Lima (60%) all year round	97
Lima Sur Desal	Lima Sur desalination plant	0.4 m^3/s to Southern Lima all year round	110
Jacaybamba Res	Jacaybamba Reservoir	1.4 m^3/s to Northern Lima and Callao in the dry season only	145
Lurin WTP	Lurin WTP	0.4 m^3/s to Southern Lima in the wet season only	25
Pomacocha Res / Huachipa WTP	Pomacocha Reservoir, expansion of Huachipa WTP, and Trans-Andean Tunnel #2	4.5 m^3/s to Central Lima (90%) and 0.5 m^3/s to Southern Lima (10%) in the dry season only	767
Pun Run Res / Chillón WTP	Pun Run Reservoir, Trans-Andean Tunnel #2, and expansion of Chillón WTP	1.9 m^3/s to Northern Lima and Callao (80%) and 0.5 m^3/s to Central Lima (20%) all year round	200
S. Antonio Res / Chillón WTP	San Antonio Escondido Reservoir and Expansion of Chillón WTP	1.1 m^3/s to Northern Lima and Callao (80%) and 0.3 m^3/s to Central Lima (20%) in the dry season; 0.8 m^3/s to Northern Lima and Callao (80%) and 0.2 m^3/s to Central Lima (20%) in the wet season	230
Ventanilla Desal	Ventanilla desalination plant	1.5 m^3/s to Northern Lima and Callao all year round	400

Cañete Trans/WTP and Chancay GW are not part of SEDAPAL's Master Plan but have been suggested as important investments to consider during the course of this analysis.

4.2 Metrics (M)

In designing its Master Plan, SEDAPAL was principally concerned with achieving water reliability as cost effectively as possible. For this analysis, SEDAPAL defines water reliability as meeting 90% of demand 90% of the time, measured monthly. In other words, water reliability is achieved if the 90th percentile of monthly met demand is at least 90%. This led to the use of two primary metrics used to compare portfolios:

1. The 90th percentile of monthly met demand (and whether this exceeds 90%), and
2. The cost of the plan (e.g. portfolio of investments).

We also evaluated the supply that would be provided to each of Lima's demand regions to estimate the cost effectiveness of individual components of Lima's Master Plan.

4.3 Uncertainties (X)

We assess three key uncertainties that challenge SEDAPAL's ability to achieve water reliability:

1. **The level of demand in the city**. Demand will be shaped principally by future population growth and per-capita water use. This varies in different districts. Overall, Lima and Callao currently have a demand of 855 Mm^3 for a population of 9.5M. Official projections of 2040 population range from 11.5M to 15.5M and per-capita water consumption from approximately 170 to 240 l/p/day, giving a range of future demand of 730 Mm^3 per year to 1,790 Mm^3 per year.[2]
2. **Future stream flows**. In the wet season, 90% of Lima's water is drawn from the Rimac, Chillón, and Lurin Rivers. The remaining 10% comes from groundwater. In contrast, in the dry season 20% comes from groundwater sources. Climate change and other factors may alter water flows, but downscaled climate projections and rainfall-runoff model are not yet available for these river basins. We explored how the system responds to potential changes in monthly stream flows proportional to the minimum (-60%) and maximum (+90%) changes in monthly precipitation, as projected in the IPCC's Fourth Assessment Report (AR4 – see Figure 4-1).[3] This approach is consistent with the principles of Decision Scaling, which seek to assess the sensitivity of investments to climate (Brown *et al.*, 2012).

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[2] This approach provides a broad range of total future water demand in Lima in order to help establish limits of the Master Plan in ensuring water reliability. For this purpose, it is not necessary to differentiate domestic, commercial, agricultural, and industrial water demand. (The latter three are much smaller than municipal demands.) A future study that includes efficiency, reuse, and demand management policies should make these distinctions, however, because different policies are appropriate for each sector. For instance, recycled water may be appropriate for non-domestic uses.

[3] The IPCC's 5th Assessment Report was not available during the time this study was conducted. Appendix A provides details on how we used these changes to develop futures.

Figure 4-1: Box plots of the changes in annual and seasonal precipitation projected by 15 climate models in 3 emissions scenarios
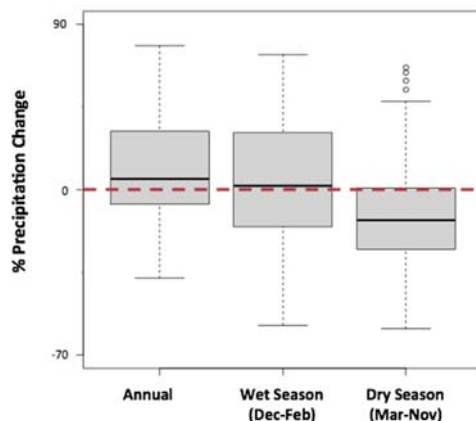

3. **Project feasibility**. SEDAPAL identified three of the candidate projects—Chosica WTP/Graton Tunnel, Cañete Trans/WTP, and Pun Run Res/Chillón WTP—as more difficult to implement than the remaining eleven. Chosica WTP/Graton Tunnel and Cañete Trans/WTP are challenging because SEDAPAL does not have full jurisdiction to implement them, and collaborative, cross-jurisdiction projects can be particularly difficult. Pun Run Res/Chillón WTP is controversial because it transfers water from the Amazon region to Lima via a tunnel. Such a project can face environmental and other hurdles. We therefore consider two future conditions—a "full project feasibility" future condition in which the three difficult projects can be implemented, and a "limited project feasibility" future condition in which they cannot.

We have developed 600 future cases from these three uncertainties: 300 demand/streamflow conditions in each of two project feasibility conditions.[4] We use Latin Hypercube Sampling (LHS) (McKay *et al.*, 1979), to develop 300 combinations of future demand and streamflow as shown in Figure 4-2.The two project feasibility conditions are the cases where more difficult projects can and cannot be implemented. Thus, each future is defined by four variables: one future level of demand, two seasonal monthly streamflow change factors, and one project feasibility condition. However, it is parsimonious to summarize streamflow in terms of the change in the dry season (March to November), as these changes have a greater influence on water reliability than changes in wet season flows (December to February) as explained in Appendix A. This allows us

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[4]In choosing the number of futures, we seek to balance the competing goals of sufficiently exploring the uncertainty space while keeping simulation run times low to allow for rapid iteration on the analysis (each run of the WEAP model takes five minutes). While the choice of 300 climate and demand futures in particular is arbitrary (for example, 250 or 500 may have worked just as well), as Figure 4-2 shows, these 300 futures efficiently cover the demand and climate uncertainty space. More importantly, our analysis shows that these futures are sufficient to identify conditions in which plans and projects achieve and fail to achieve water reliability. (Hypothetically, if there were ambiguity about performance in a particular part of the uncertainty space, additional sampling in that region could add clarity.)

to show the 300 futures in two dimensions: demand and changes in dry season streamflow.

Figure 4-2: 300 futures that are each a combination of demand and change in streamflow
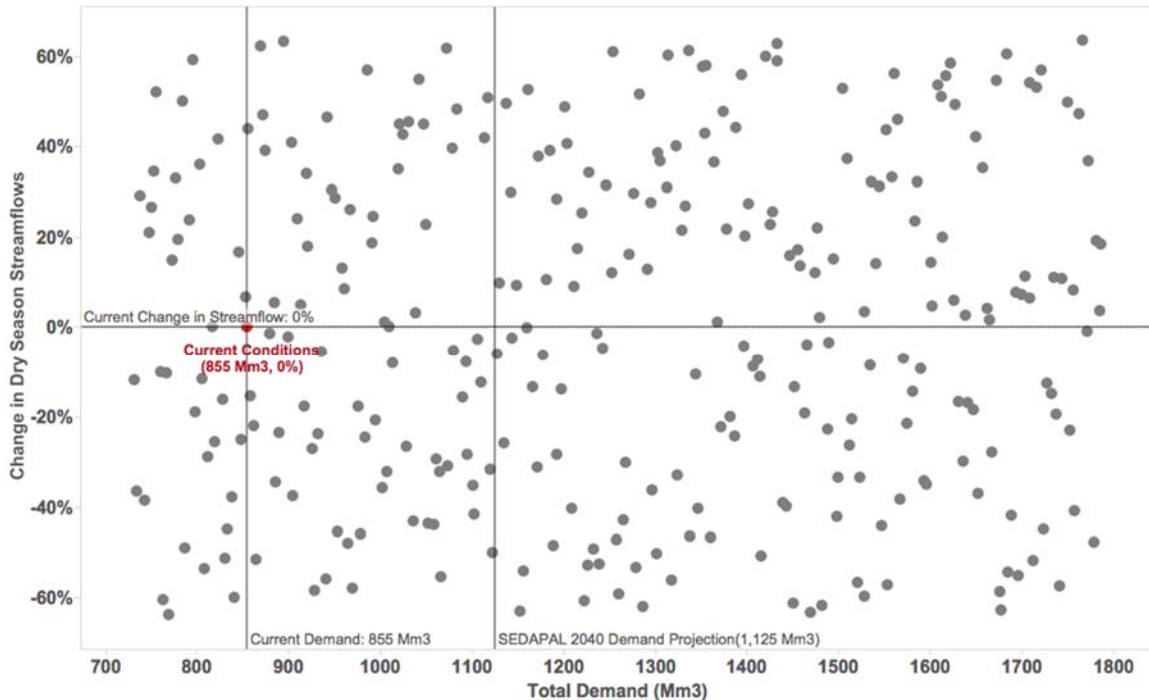
4.4 Models (R)

The analysis uses two modeling tools. A model of the water management system is used to evaluate the performance of the SEDAPAL system with and without new projects. An interactive, analytic decision support tool provides interactive visualizations of key results and supports the development of portfolios of projects based on individual projects' cost effectiveness and implementation and cost constraints.

4.4.1 Water Management Model

This project uses a water-planning model developed in the Water Evaluation and Planning (WEAP) modeling environment. WEAP is an industry-standard platform and can represent major water supply and demand elements of a water management system in a transparent and user-friendly way. This allows SEDAPAL planners and decision makers to interact directly with the model, which helped build trust in its outputs and intuition about its results.

As summarized by Joyce et al. (2010):

> ... [t]he WEAP system is a comprehensive, fully integrated river basin analysis tool. It is a simulation model that includes a robust and flexible representation of water demands from different sectors, and the ability to program operating rules

for infrastructure elements such as reservoirs, canals, and hydropower projects (Huber-Lee *et al.*, 2006; Purkey *et al.*, 2007; Yates *et al.*, 2005a, 2005b, 2008). Additionally, it has watershed rainfall-runoff modeling capabilities that allow all portions of the water infrastructure and demand to be dynamically nested within the underlying hydrological processes. This functionality allows the modeler to analyze how specific configurations of infrastructure, operating rules, and operational priorities will affect water uses as diverse as instream flows, irrigated agriculture, and municipal water supply under the umbrella of input weather data and physical watershed conditions. This integration of watershed hydrology with a water systems planning model makes WEAP ideally suited to study the potential impacts of climate change and other uncertainties internal to watersheds.

The SEDAPAL WEAP model represents Lima's system through a series of demand and supply nodes, connected via transmission links representing either natural streams or engineered canals. The water demand in the Metropolitan area is represented by a demand node for each of Lima's four main regions: Central Lima, Eastern Lima, Southern Lima, and Northern Lima and Callao. The model contains all existing water infrastructure, including five reservoirs in the Alto Mantaro, two groundwater basins, and all canals and transfer tunnels of the Marca I, II, and V,[5] including a trans-Andean tunnel. The model also contains the existing water treatment plants of Atarjea and Chillón. Additionally, each of the 14 proposed Master Plan projects can be modeled individually or in different combinations.

The WEAP model takes as input (i) monthly hydrological series, (ii) the depth, levels, and operations of the reservoirs, and their evaporation, (iii) the design capacity of all investments, and (iv) different demand scenarios, divided per demand region. Besides water supply to the different areas of the city, the model also reports monthly water levels in the reservoirs, groundwater extraction levels, and unmet demand. Figure 4-3. shows a screenshot of the schematic of SEDAPAL's water management system within WEAP.

This is SEDAPAL's first model of the water system supplying Lima Callao, and they will continue to use it for their planning after this project. Before the development of this model, SEDAPAL's project prioritization was based primarily on experts' considerations and the additional supply sought in different parts of the city. SEDAPAL did not have tools that allowed for an integrated and dynamic analysis of different projects. SEDAPAL's continuous involvement in the model's development helped both build confidence in the model and its results, and increase the likelihood of a successful technology transfer of the model to SEDAPAL for its future analyses.

We developed a code to evaluate the WEAP model on the Amazon cloud, allowing the simultaneous running of up to a hundred cases at once. First, we ran the baseline (i.e., without Master Plan) under the 300 water supply and demand futures we created, then the baseline plus one individual project at the time, and finally, the first selection of portfolios to identify which ones performed better across these futures.

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[5] The three Marcas indicate the sequenced construction of the investments: Marca I began in 1960s, Marca II at the end of 1990s, and Marca III-V in 2000s.

We post-processed the WEAP outputs to create a database with the performance of the system (e.g., 90th percentile of met demand) for each project, portfolio, and region under the 300 future combinations of streamflow and demand changes.

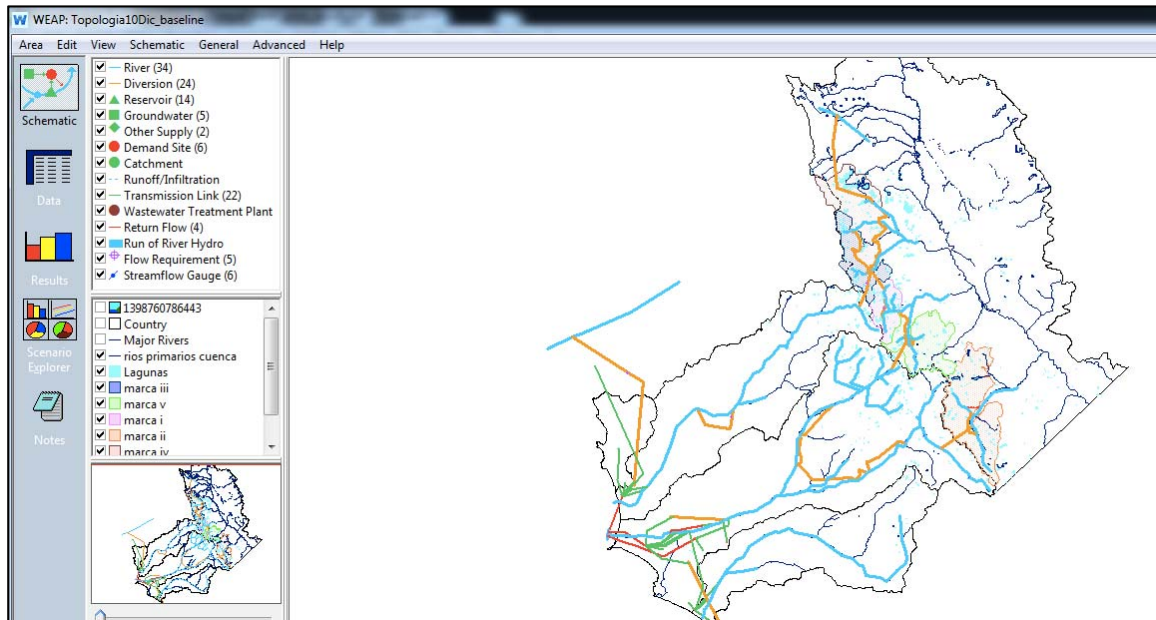**Figure 4-3. WEAP model schematic of SEDAPAL's water management system**

We developed a code to evaluate the WEAP model on the Amazon cloud, allowing the simultaneous running of up to a hundred cases at once. First, we ran the baseline (i.e., without Master Plan) under the 300 water supply and demand futures we created, then the baseline plus one individual project at the time, and finally, the first selection of portfolios to identify which ones performed better across these futures.

We post-processed the WEAP outputs to create a database with the performance of the system (e.g., 90th percentile of met demand) for each project, portfolio, and region under the 300 future combinations of streamflow and demand changes.

4.4.2 Interactive, Analytic Decision Support Tool

An interactive, analytic decision support tool was developed using Tableau—a business analytic software system.[6] This tool helps visualize results from the simulation model, allowing SEDAPAL planners to explore across the hundreds of cases evaluated. It also provides the means for developing portfolios using an optimization module developed in the R statistical programming language.[7] The optimization module estimates the optimal combination of projects that maximize the supply of water to the SEDAPAL service area for each future, subject to a budget constraint and project

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[6] Information about Tableau can be found on the developers website--www.tableausoftware.com.

[7] R is available from http://www.r-project.org/.

feasibility specifications. The decision support tool then reports the cumulative effects of each optimal portfolio and supports the comparisons of projects selected for each portfolio. The analytical figures in this paper are screenshots from the tool. It is available online at https://goo.gl/BRojPW.

5 Baseline Vulnerability

We present the results of this study by stepping through a series of questions about the proposed investments and trade-offs among portfolios. In this section, we assess the performance of the baseline vulnerabilities of the current system and the Master Plan. In section 6, we generate and evaluate portfolios of projects under different budgets. In section 7, we use these portfolios to develop a decision tree that guides SEDAPAL through an adaptive set of no-regret investments.

5.1 Does Lima's Current System Achieve Water Reliability?

Lima's current water demand is approximately 855 Mm^3. Using WEAP to evaluate the performance of the current system under current and historical flow conditions and current demand reveals that SEDAPAL's existing system just achieves water reliability. Lima meets 90.4% of the demand 90 percent of the time. (Recall that water reliability is achieved when the 90th percentile of monthly met demand is above 90%.)

5.2 Could SEDAPAL Achieve Future Water Reliability Without Further Investment?

It is useful to assess whether Lima could achieve water reliability in the future without the proposed projects. This analysis reveals the need for future investments.

We assessed whether SEDAPAL could achieve future water reliability by evaluating the performance of the current system in WEAP in each of the 300 plausible demand and streamflow futures.

Without the proposed projects, SEDAPAL cannot achieve water reliability in 2040 if demand exceeds approximately 920 Mm^3, regardless of future flows. This is somewhat more than current levels of demand but much less than SEDAPAL's projection for 2040 demand of 1,125 Mm^3 and far less than the highest plausible demand of 1,800 Mm^3. If future flows decrease, SEDAPAL may not be able to ensure water reliability even if future demand were less than today's demand. These results confirm SEDAPAL's need to undertake major investments in either new water supply or efficiency and demand management to achieve water reliability for Lima.

Figure 5-1 shows the results. Each mark represents a future. The size of each mark indicates the 90th percentile of monthly met demand—smaller marks indicate lower met demand and hence worse performance. Marks are also colored differently—blue circles

indicate that water reliability is achieved in that future and orange open circles indicate that reliability is not.

Without the proposed projects, SEDAPAL cannot achieve water reliability in 2040 if demand exceeds approximately 920 Mm^3, regardless of future flows. This is somewhat more than current levels of demand but much less than SEDAPAL's projection for 2040 demand of 1,125 Mm^3 and far less than the highest plausible demand of 1,800 Mm^3. If future flows decrease, SEDAPAL may not be able to ensure water reliability even if future demand were less than today's demand. These results confirm SEDAPAL's need to undertake major investments in either new water supply or efficiency and demand management to achieve water reliability for Lima.

Figure 5-1: Performance of the current system in each of 300 futures
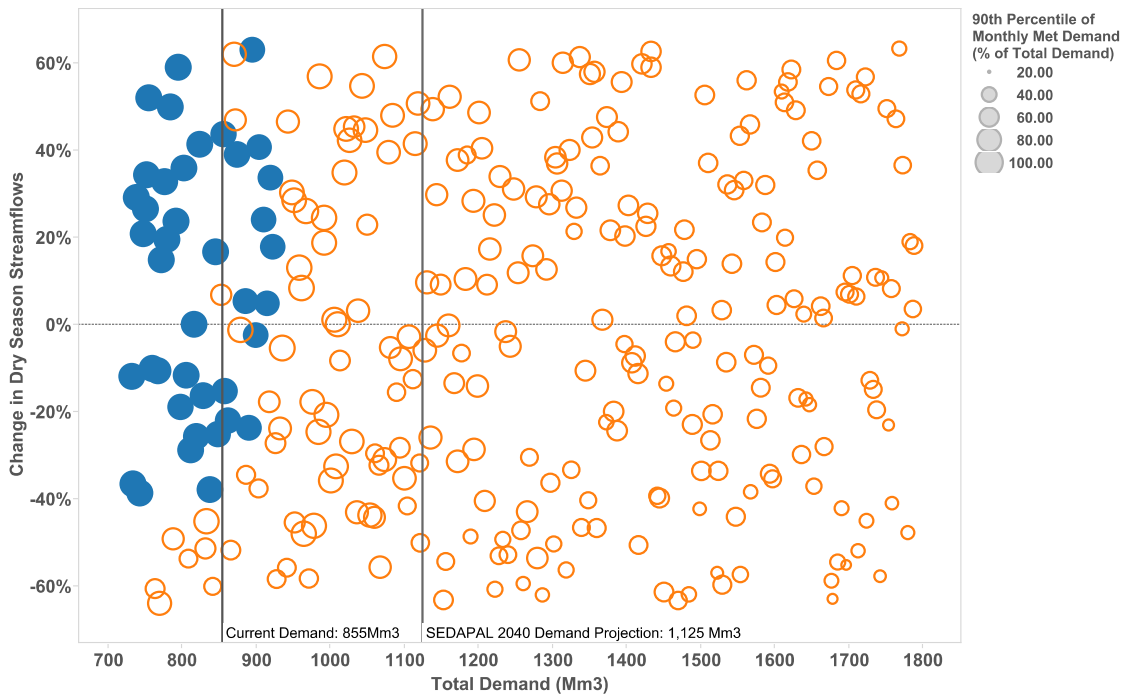
Note: Blue filled circles indicate futures in which water reliability is achieved; orange unfilled circles indicate futures in which it is not achieved. The size of the mark indicates the 90th percentile of monthly met demand.

5.3 Would Implementing the Complete Master Plan Ensure Future Water Reliability?

We evaluate the performance of all proposed 14Master Plan projects together in WEAP in each future.[8] We call this the "All Projects" portfolio. This analysis reveals the highest degree of water reliability that could be expected with the proposed investments.

Figure 5-2 shows the performance of the All Projects portfolio. All Projects increases the 90th percentile of monthly met demand (nearly all points are larger). Also, with All Projects, SEDAPAL can achieve water reliability in many more futures (there are many more blue points). As we might expect, there is also a clear interaction between future streamflow and future demand in determining water reliability. If future streamflow increases (e.g., due to a favorable climate), it can achieve water reliability up and beyond forecasted levels of demand. However, if streamflow declines or demand is higher than forecast, SEDAPAL may need to invest in aggressive efficiency and demand management in order to achieve water reliability.

Figure 5-2: Performance of the All Projects portfolio in each of 300 futures
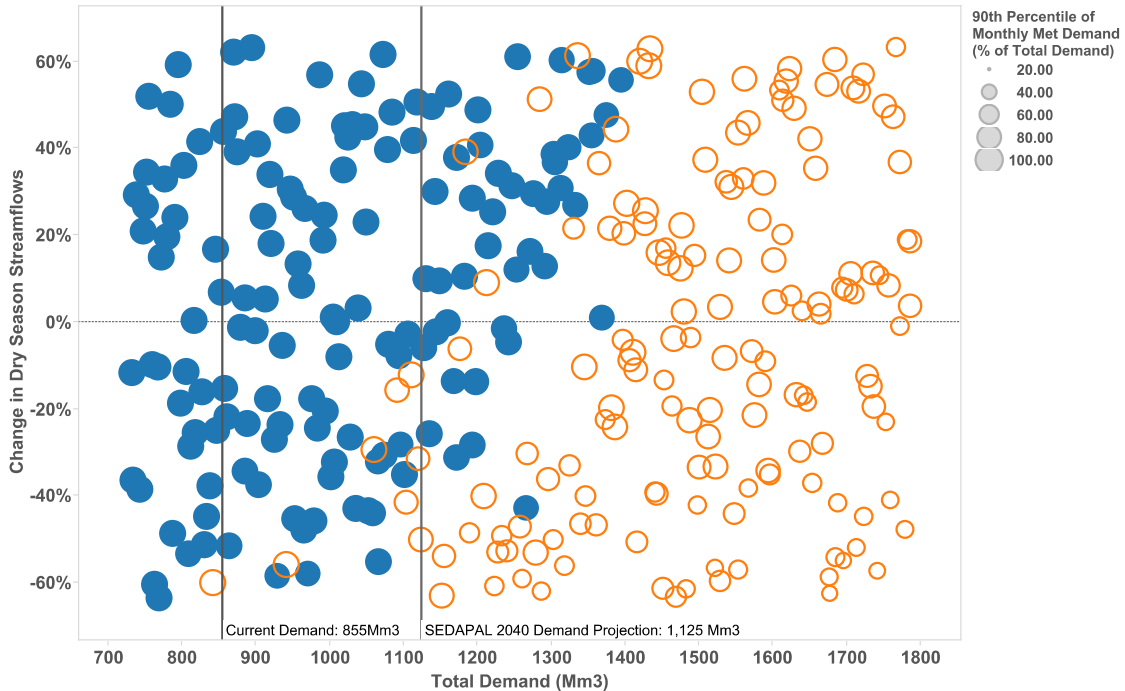

Note: Blue filled circles indicate futures in which water reliability is achieved; orange unfilled circles indicate futures in which it is not achieved. The size of the mark indicates the 90th percentile of monthly met demand.

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[8] Two projects, S. Antonio Res / Chillón WTP and Pun Run Res / Chillón WTP, are mutually exclusive. Only one or the other can be constructed, not both, because they are duplicative investments that supply water to the WTP Chillón II. Our analysis shows that implementing San Antonio instead of Pun Run nearly always leads to better performance than vice versa, and therefore the "All Projects" portfolio results shown consist of 13 projects including San Antonio and excluding Pun Run.

6 Portfolio Development and Analysis

Implementing all 14 projects can ensure water reliability in many but not all plausible futures. In some cases, however, a smaller set of projects may be sufficient (e.g., if demand or streamflow are favorable), necessary (e.g., if some projects are too difficult to implement), or preferable (e.g., for cost savings). Developing and evaluating portfolios of projects—i.e., combinations of the 14 individual projects—can help SEDAPAL understand trade-offs between performance and cost and reveal how to prioritize among the full set of potential investments.

6.1 How Can We Develop Portfolios For A Robust Implementation of the Master Plan?

In this project, we use two smaller budgets—75%, and 50%—to develop and assess the performance of smaller portfolios. For these two budgets and the full budget case, we identify the portfolios that achieve the greatest water reliability under different project feasibility, demand, and streamflow conditions. These portfolios form the basis of a decision tree that guides no-regret, adaptive investment decision making for SEDAPAL.

We use the decision support tool to first identify optimal portfolios for each future given budgetary constraints. To do this, the tool maximizes the amount of water that would be supplied cumulatively by the projects in a given portfolio, for a given budget. This approach generally selects the projects that are most cost effective—those that deliver the most supply for a given level of investment.

As described in Figure 4-3., each project is designed to supply a particular amount of water to different areas of the city and in different seasons. However, the actual supply delivered may be less than designed if the future is relatively dry and there is insufficient water available, or if the future has relatively low demand and not all of the available supply needs to be delivered. We estimate these future-specific effects by simulating in WEAP each project individually in each future. Figure 6-1 shows box plots of each project's monthly supply deliveries across the 300 futures for all of Lima, costs, and cost-effectiveness. It shows that Atarjea WTP is more cost effective than other projects by several orders of magnitude, given its large deliveries and low cost. It also shows that Atarjea WTP, Autisha Res/Lurigancho WTP, Casacancha Res, and Pun Run Res/Chillón WTP have negative deliveries to the city in some futures. This is because multiple parts of the system draw upon the same limited sources of water. In some futures, these four projects may divert water from other parts of the system that would have had greater supply deliveries.

**Figure 6-1:Projects' supply deliveries, costs, and cost-effectiveness across 300 futures**
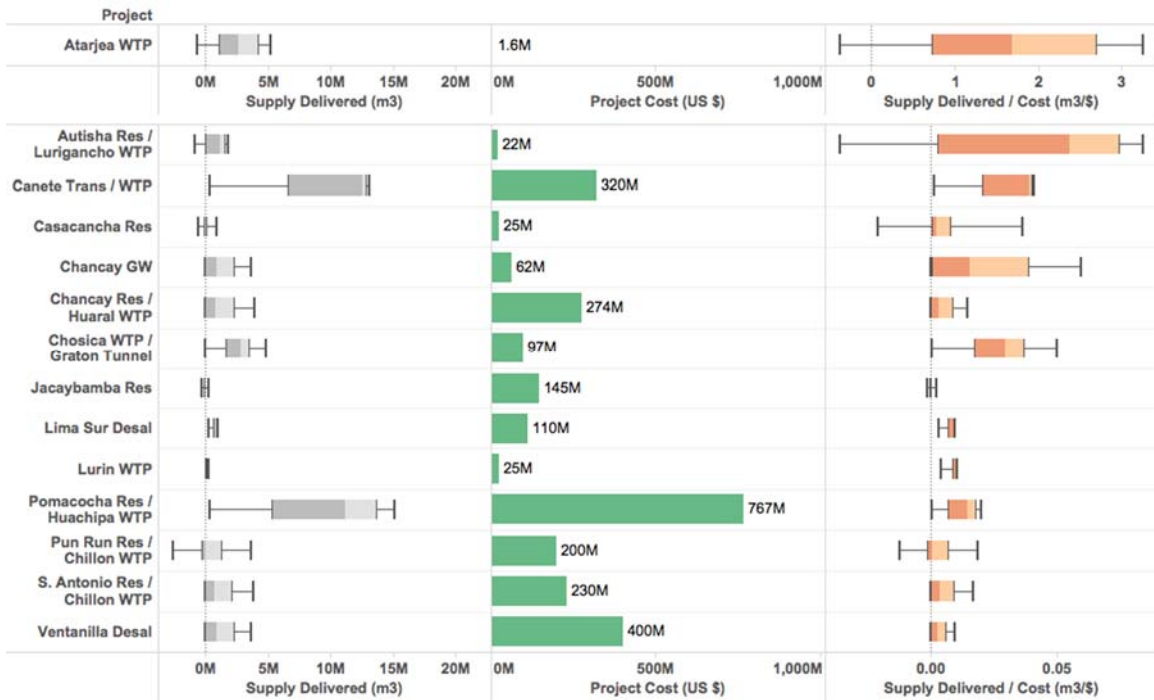
Note: The Atarjea WTP is several orders of magnitude more cost effective than other projects. We show it on a separate scale so that the differences in cost effectiveness among other projects are visible. The scales for supply delivered and project cost are the same for all projects.
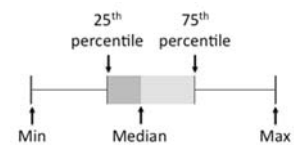
Projects may also supply different amounts of water to regions in different futures, as Figure 6-2 illustrates for two example futures. For instance, in a wetter climate with higher demand, Chosica WTP/Graton Tunnel supplies water to Eastern Lima. When the climate is drier and demand is lower, it supplies water to Central Lima instead because, in this future, unmet demand is higher. Therefore, the portfolios calculated by the decision support tool may differ across each future.

In theory, this process could produce a unique portfolio for each future (there are over 16,000 possible portfolios). In practice, the tool's optimizer identifies the same portfolio as bringing highest yields for many futures. Furthermore, the portfolios suggested by the tool may not necessarily provide the most water when the projects of the portfolios are evaluated together by WEAP. This is because the supply delivered by a portfolio of projects (evaluated together) may be different from the sum of their individually calculated supply because of the interactions among projects.

Figure 6-2: Projects' monthly water supply deliveries to different regions of Lima in two futures
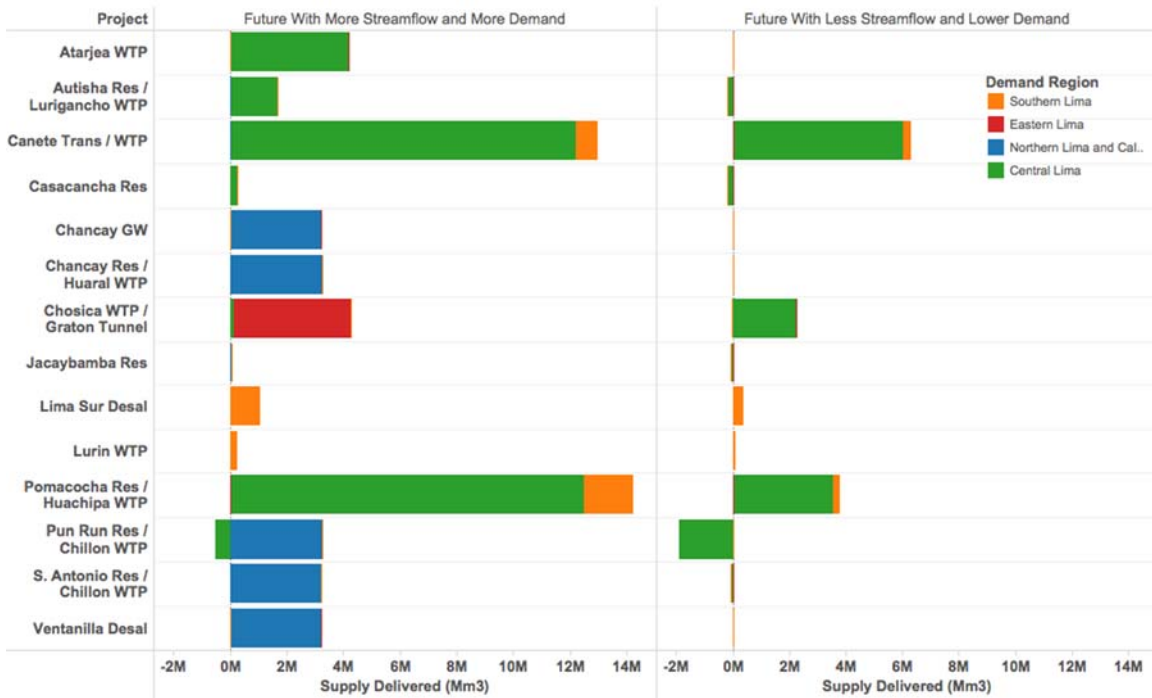

Given limited computational time, we do not run all suggested portfolios across all futures. Instead, we re-evaluate in WEAP the most frequently suggested portfolios that, together, cover at least 90% of futures. We then look across futures to find broad sets of future conditions in which a given portfolio is best. Not surprisingly, different portfolios are optimal under the two different project feasibility conditions since the subset of available projects is different in each case. However, we find that for each combination of budget and project feasibility condition, a single portfolio performs as well or better than all others across all futures.

For example, for the 75% budget in which all projects are feasible, the optimizer suggests five unique portfolios (named A-E) across the 300 streamflow and demand futures. Figure 6-3 shows the portfolios that achieve reliability in each future when evaluated in WEAP. Portfolio C achieves reliability in more futures than any other portfolio and in every future where reliability is possible with the given investments. Thus, Portfolio C is the best portfolio for this budget and feasibility condition.

Figure 6-3: Portfolios that achieve water reliability in each future under a 75% budget and full project feasibility
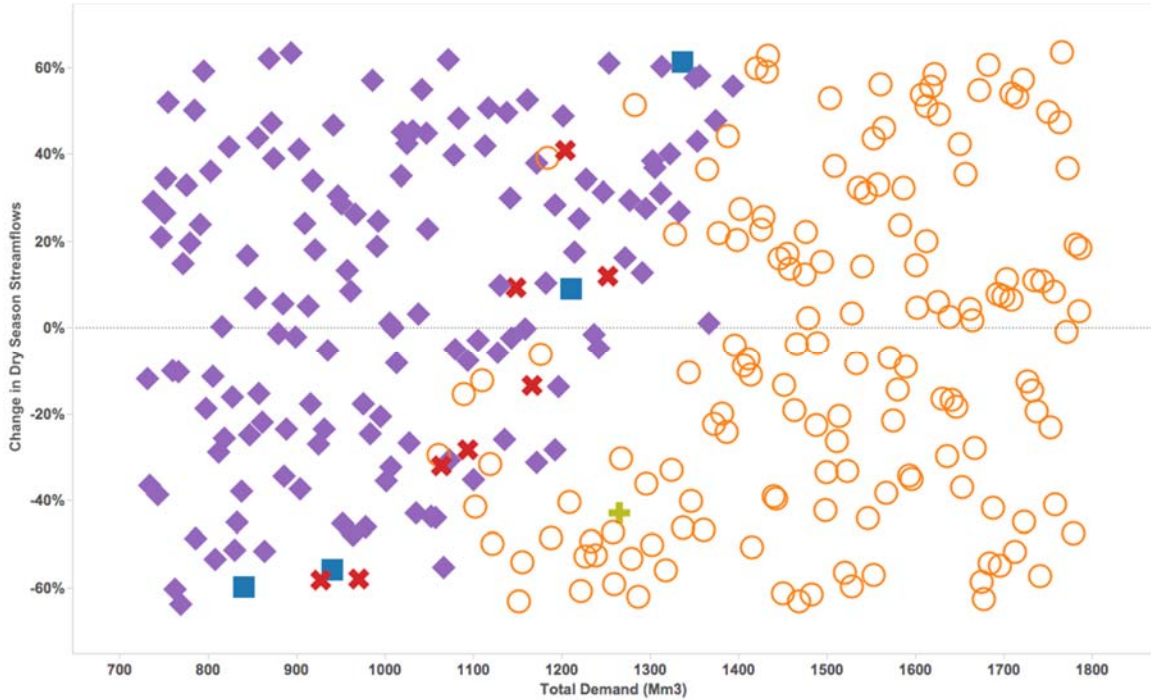
6.2 Can Smaller Portfolios Achieve Water Reliability More Efficiently Than Implementing All Projects?

As shown in Figure 5-2 above, implementing all projects does not lead SEDAPAL to meet its objectives under many higher demand and drier futures. In these cases, additional investments would be needed. Furthermore, in the futures in which the SEDAPAL's objectives are met, it is possible that they could be met with fewer investments, thus freeing up resources that could be used to expand the robustness of SEDAPAL's plan.

Figure 6-4 shows the performance of the best portfolio for each budget when projects are fully feasible and, for comparison, the performance of the All Projects and Current System (i.e. No Project) portfolios. The box plots summarize the 90th percentile of monthly met demand across all 300 climate and streamflow futures. Water reliability is achieved if this is above 90%, in the shaded blue region.

Figure 6-4: Summary performance portfolios with full project feasibility
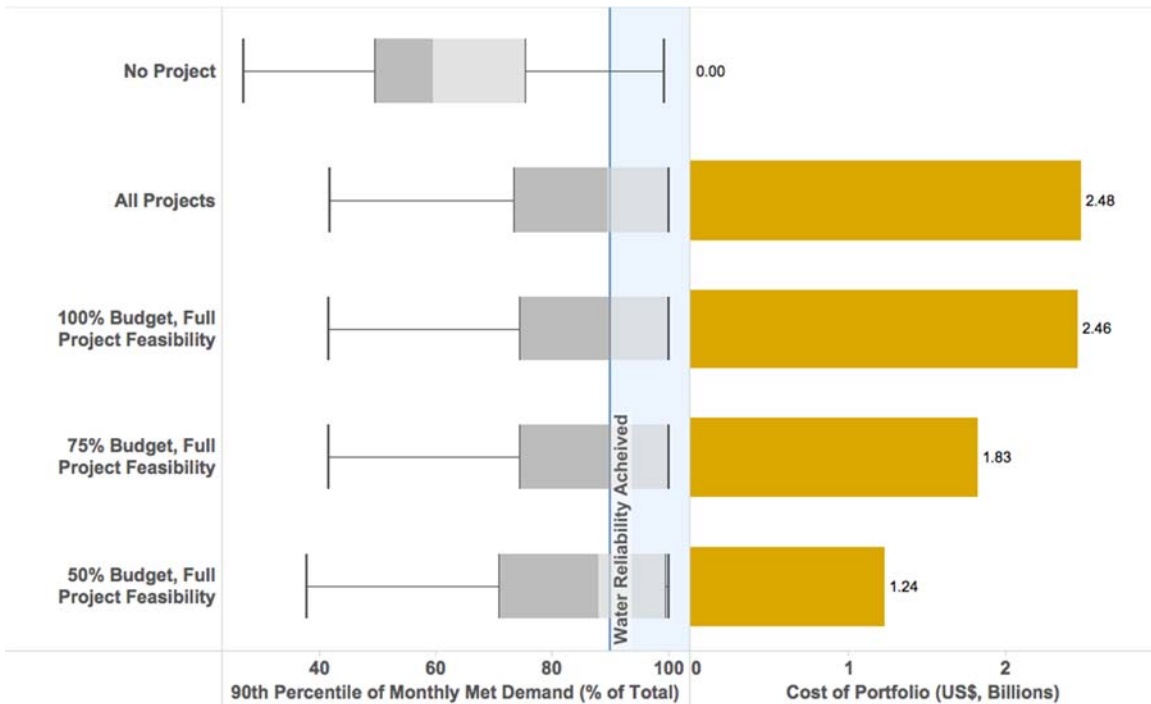
First, we can see that all portfolios are much better at meeting demand than the current system across the range of futures. Second, the portfolio that is best for 100% budget and full project feasibility (third row in the figure) differs from the All Projects portfolio (second row in the figure). The former omits Autisha Res / Lurigancho WTP because in drier climates this project reduces the net supply delivered and in wetter climates its added supply is not enough to change whether water reliability is met or not in any future.[9] The cost savings of US $22 million is a secondary benefit.

Rows 3-5 in Figure 6-4 summarize the performance of the portfolios for 100%, 75%, and 50% budgets, in the condition that all projects can be implemented. There is no difference in performance between 100% and 75% budget. The main difference of course is the budget—US$2.48B vs. US$1.86B.[10]

Examining the projects in each portfolio and the regional effects explains why there is no decline in performance when reducing the budget. Figure 6-5 shows the projects in the most robust portfolio when all projects are feasible. The portfolios under 100% and 75% budgets when all projects are available (the first two portfolios) are very similar. The

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[9]Autisha Res/Lurigancho WTP and Atarjea WTP both draw on resources from the Rimac River. Atarjea WTP delivers water immediately while, with Autisha Res/ Lurigancho WTP stores water in the reservoir before releasing it to the Lurigancho WTP. This makes Atarjea WTP more effective at meeting the demand, and implementing Autisha Res/Lurigancho WTP in these conditions reduces water reliability. In other futures, where Autisha Res/Lurigancho WTP increases the supply delivered, these deliveries rarely make the difference between failing to achieve and achieving water reliability. In combination, with 100% budget and full project feasibility it is preferable to omit Autisha Res/Lurigancho WTP.

[10]The actual cost of the most cost-effective portfolio with 75% budget is 1.83B.

only difference is that S. Antonio Res / Chillón WTP and Ventanilla Desal are not included in the 75% budget portfolio. Both of these projects serve Northern Lima, but other projects that are in the portfolio also serve this demand area—Chancay GW, Chancay Res / Huaral WTP, and Jacaybamba Res. Together, these three projects more cost effectively and fully meet the demand in Northern Lima in all plausible streamflow and demand futures. Therefore, the additional supplies to Northern Lima from S. Antonio Res / Chillón WTP and Ventanilla Desal are not needed before 2040 and can be safely delayed beyond this time horizon.

Figure 6-4 does show that there is some decline in the performance from a 75% budget to a 50% budget, again assuming all projects are potentially implemented. As Figure 6-5 indicates, the most robust portfolio with a 50% Budget is the same as the 75% budget portfolio, but without Chancay GW, Chancay Res/Huaral WTP, Jacaybamba Res, and Lima Sur Desal. Without these three projects, this portfolio does not supply any additional water to Northern Lima and Callao over the current system. The decrease in overall met demand relative to the 75% budget portfolio is modest because Central Lima, which has the largest share of demand, is still well supplied by this portfolio. However met demand in Northern Lima and Callao declines significantly.

Figure 6-5: Portfolios for 100%, 75%, and 50% budgets with full project feasibility
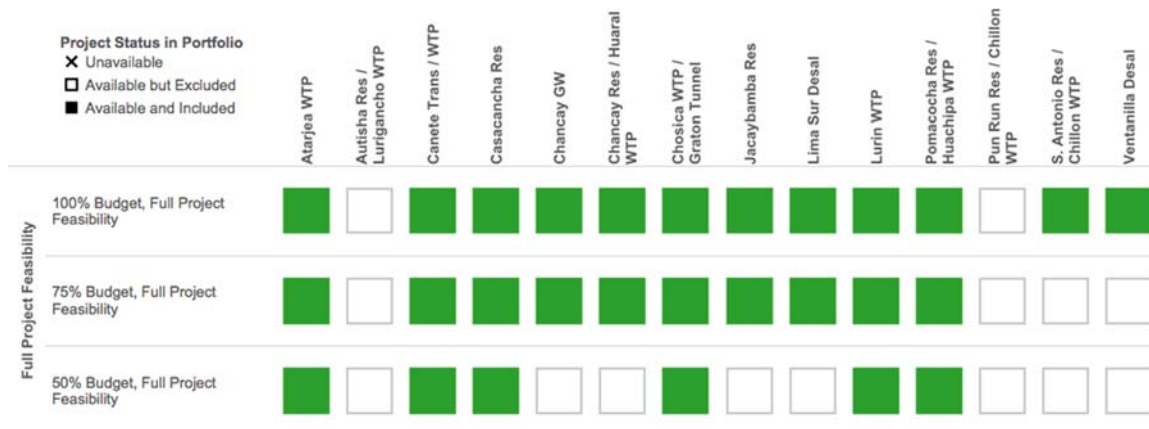
Figure 6-6 summarizes these trade-offs between cost and water reliability across all streamflow and demand conditions, when all projects are feasible. We can draw several conclusions. First, a portfolio of six of the 14 projects (Atarjea WTP, Cañete Trans/WTP, Casacancha Res, Chosica WTP / Gratón Tunnel, Huachipa WTP/ Pomacocha Res, and Lurin WTP) can achieve water reliability at a cost of US $1.24 B (50% of the full Master Plan cost) if future demand is near SEDAPAL's projection and historical streamflow conditions persist. If streamflow increases, this portfolio can accommodate more demand while still ensuring reliability, but if streamflow decreases, demand must be less than SEDAPAL projections for 2040.

Second, in a few futures where demand is higher or streamflow is lower, adding four projects—Chancay GW, Chancay Res / Huaral WTP, Jacaybamba Res, and Lima Sur Desal—can achieve water reliability for a total cost of US $1.83 B (75% of the full master plan cost). Third, there are no futures in which implementing the remaining two

projects—S. Antonio Res / Chillón II WTP and Ventanilla Desal—helps achieve water reliability. These projects could be delayed until after 2040 without reducing system performance. Finally, there are many plausible futures in which the proposed projects cannot achieve reliability. In these futures, demand is slightly higher than SEDAPAL projects but streamflow is much less than it has been historically; or, demand is much higher SEDAPAL projects. In these cases, SEDAPAL would need to invest in efficiency and demand management to achieve its reliability goals.

Figure 6-6: Water reliability and cost trade-offs when all projects are feasible
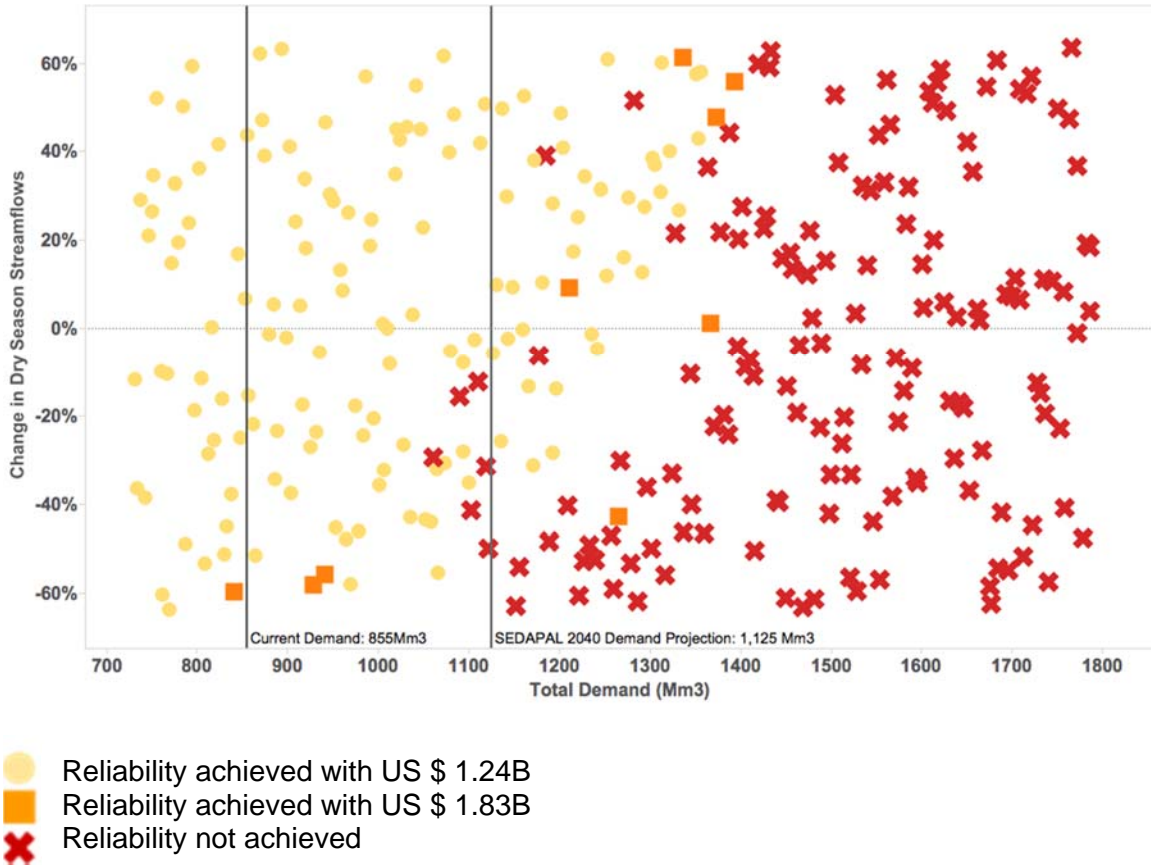
6.3 What Are the Implications If Not All Projects Are Feasible?

We next examine the implications if SEDAPAL is unable to complete the three projects it identified as more difficult to implement than others—Cañete Trans/WTP, Chosica Graton, and Pun Run Res/Chillon II WTP. In this case, the portfolios constructed with the 100%, 75%, and 50% budget constraints cannot include any of these three projects, as shown in the portfolios in Figure 6-7. (This figure repeats the first three rows of Figure 6-5.)

Figure 6-7: Portfolios for 100%, 75%, and 50% budgets with full and limited project feasibility
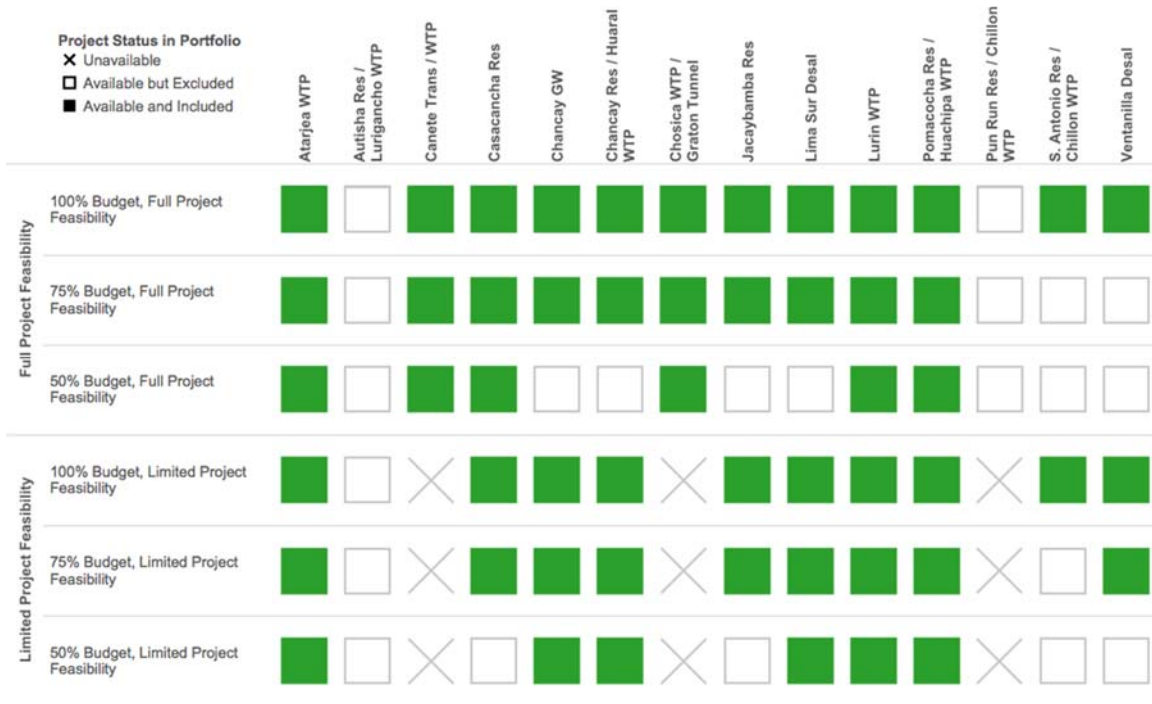
Figure 6-8 shows a significant decrease in water reliability relative to the full project feasibility conditions (This figure repeats the first five rows of Figure 6-4.) This occurs for two reasons First, Cañete Trans/WTP supplies more water to Central Lima—the largest demand area—than any other project. Second, Chosica WTP/ Graton Tunnel is the only project that supplies water to Eastern Lima, and it also provides water to Central Lima. Thus, these two projects play a key role in meeting demand in the city and SEDAPAL should seek ways of reducing the barriers to implementing these projects. In contrast, Pun Run Res/ Chillon II WTP supplies water to Northern Lima and Callao, sometimes by diverting water from Central Lima. As such, it sometimes has a negative impact on water reliability given that Central Lima has much larger demand. Moreover, Pun Run Res/ Chillon II WTP and S. Antonio Res / Chillón WTP are mutually exclusive projects and in nearly every future, the latter is preferred to Pun Run Res. Therefore, excluding Pun Run because of its low feasibility status does not affect water reliability in the city.

Figure 6-8: Summary of portfolio performance with full and limited project feasibility
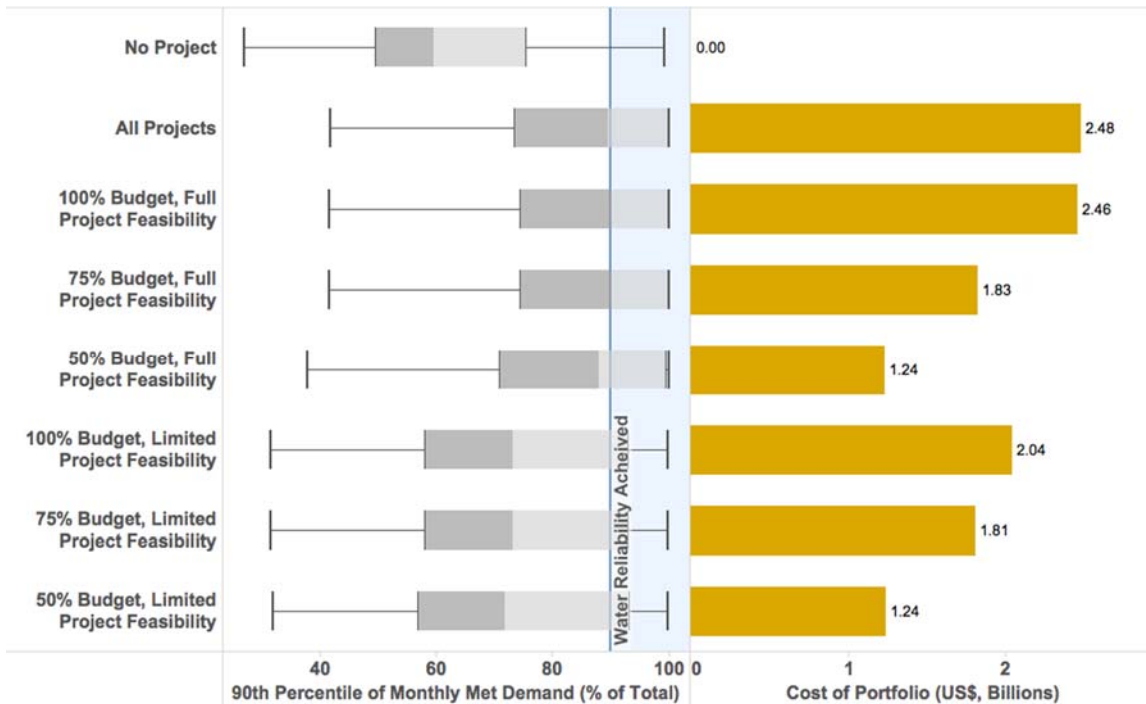
As Figure 6-8 shows, there is essentially no performance effect of decreasing the budget from 100% to 50% once these projects are removed—the box plots of performance are nearly identical. Figure 6-9 shows this in further detail with trade-offs between cost and water reliability. First, without Cañete Trans/WTP and Chosica Res/Graton Tunnel, water reliability can only be achieved if demand is lower than SEDAPAL's projections or, if the future is particularly dry, if demand is lower than it is today. Second, in futures where water reliability is still possible, it can almost always be achieved with six projects -- Atarjea WTP, Chancay, Chancay / Huaral, Huachipa WTP / Pomacocha Res, Lima Sur Desal, and Lurin WTP. This portfolio costs US $1.24B, 50% of the total Master Plan cost. Third, adding the remaining projects with a 75% or 100% budget only ensures water reliability in one of the 300 futures. Thus, if SEDAPAL cannot implement Chosica Res/ Graton Tunnel and Cañete Trans/WTP, it should forego implementing the eight remaining proposed projects and instead invest in efficiency and demand management.

Figure 6-9: Water reliability and cost trade-offs when project feasibility is limited

Reliability achieved with US $ 1.24B
Reliability achieved with US $ 1.83B
Reliability not achieved
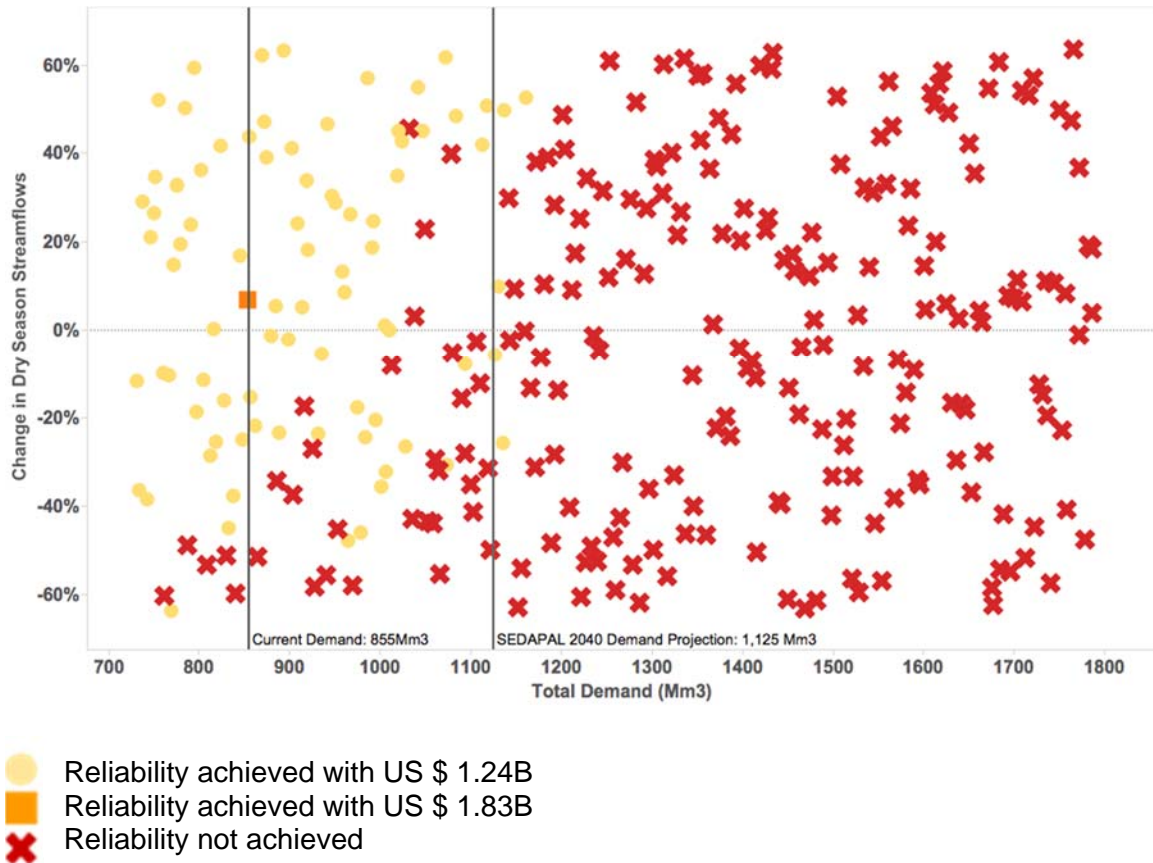
7 A Robust, Adaptive Strategy of No-Regret Investments

The analysis of portfolios in section 6 reveals that, in many cases, SEDAPAL can use smaller and less expensive portfolios to achieve water reliability across climate and demand conditions. Figure 7-1 shows ranges of future streamflow and demand conditions in which each of the six portfolios (shown in Figure 6-7) can achieve water reliability. The portfolios denoted within each region have identical performance. Note, however, that each region is a convex hull: it is the smallest convex polygon that can be drawn around the futures in which a portfolio achieves water reliability. Because the separation between successful and failed futures overlaps, there are futures within each region for which the portfolios listed do not achieve reliability.

Figure 7-1: Future conditions in which different portfolios can achieve water reliability
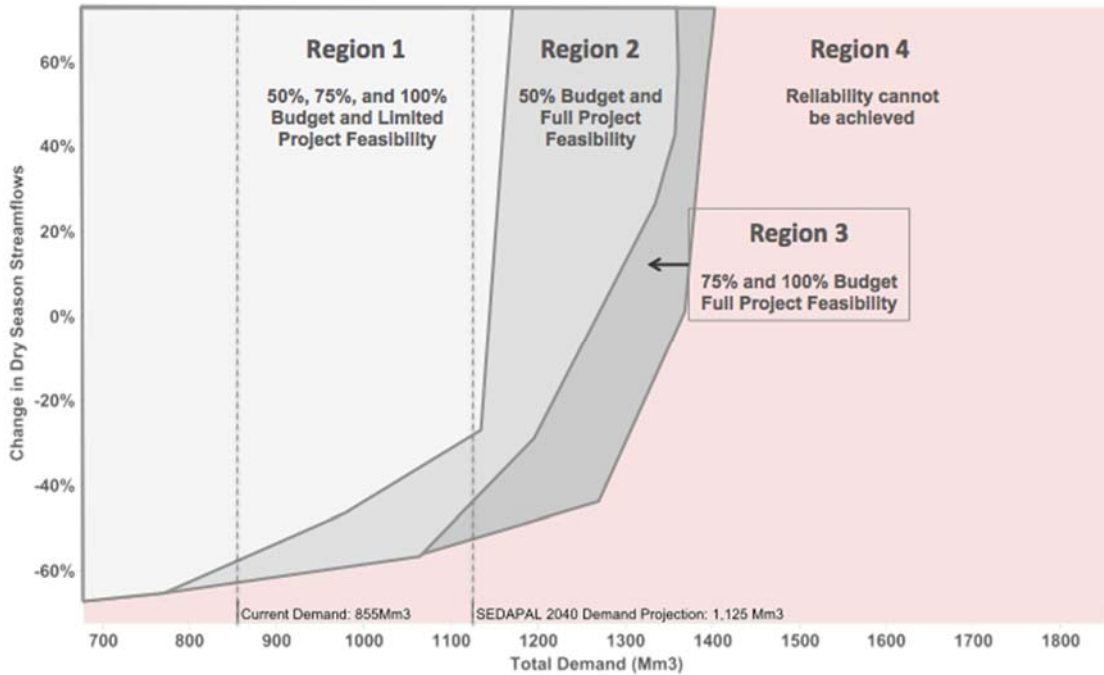
In a future with limited project feasibility, SEDAPAL could achieve water reliability with the 50% budget portfolio if streamflow and demand fall in Region 1. If they are outside of this region, implementing additional projects through the 75% and 100% budget portfolios confers no additional benefit. Instead, SEDAPAL will need to pursue additional options outside of the proposed projects.

In a future with full project feasibility, SEDAPAL could achieve reliability with the 50% budget portfolio if future climate and demand conditions fall in Regions 1 or 2. If climate and demand falls in Regions 1, 2 or 3, SEDAPAL could achieve reliability with the 75% budget portfolio. If they fall in region 4, however, SEDAPAL cannot achieve reliability, and there is no added benefit from pursuing the 100% portfolio budget. Instead, SEDAPAL should implement the 75% budget portfolio to maximize water deliveries and then pursue additional options outside of the proposed projects.

When framed this way, SEDAPAL would know which portfolio to pursue if it could predict future feasibility, streamflow, and demand conditions. Yet these are deeply uncertain. How can SEDAPAL embark on an investment strategy when it cannot predict the future?

The answer lies in identifying no-regret projects for near-term implementation and then crafting an adaptation process for implementing additional investments as conditions are revealed over time. Figure 7-2 shows the portfolios that most efficiently meet water reliability in regions 1, 2, and 3 of Figure 7-1. These are the 75% Budget, Full Project Feasibility; 50% Budget, Full Project Feasibility; and 50% Budget Limited Project Feasibility. Figure 7-2 shows that three projects—Lurin WTP, Atarjea WTP, and Pomacocha Res/Huachipa WTP—are included in all of the portfolios. SEDAPAL can

confidently implement these projects now, regardless of project feasibility, streamflow, and demand conditions. It also shows that SEDAPAL could defer four projects to beyond 2040, as they are not part of any of these portfolios: Autisha Res/Lurigancho WTP, Pun Run Res/Chillon WTP, S. Antonio Res/Chillon WTP, and Ventanilla Desal.

**Figure 7-2: Portfolios for 100%, 75%, and 50% budgets with full and limited project feasibility**
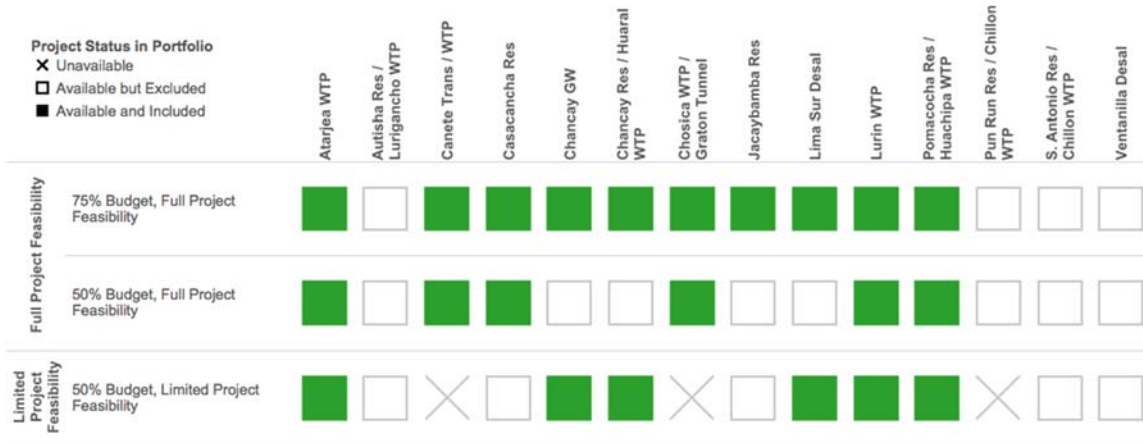
An adaptive decision tree of no-regret options enables SEDAPAL to implement its proposed projects robustly. Figure 7-3 shows this tree. It consists of a sequence of no-regret investments (squares), conditions that SEDAPAL should monitor (diamonds), and signposts that SEDAPAL should look for to trigger new no-regret investments (branches).

The root of the tree is the far left green square and represents the three no-regret projects SEDAPAL can implement in the near term. Next, SEDAPAL should monitor and assess the feasibility of implementing Cañete Trans/WTP and Chosica WTP/Graton Tunnel, as these are more difficult to implement but also significantly increase water reliability. Because SEDAPAL and other stakeholders may be able to influence the feasibility of these projects, this condition should be monitored and addressed in the mid-term. The decrease in water reliability without Cañete Trans/WTP and Chosica WTP/Graton is significant. If these projects turn out to be feasible, SEDAPAL follows the top branch to the investment node marked "mid-term, full feasibility." It lists three additional projects that are common to the full-feasibility portfolios: Cañete Trans/WTP, Casacancha Res, and Chosica Res/Graton Tunnel. These projects are no-regret and SEDAPAL could implement them even though additional uncertainties remain. At this point, SEDAPAL would have implemented the 50% budget, Full Project Feasibility portfolio.

In the longer term, SEDAPAL should monitor streamflow and demand and assess whether these conditions would fall in Region 2, 3, or 4 of Figure 7-1. If it falls in Region 2, then it is likely that no further action would be necessary since the 50% Budget, Full Project Feasibility portfolio achieves water reliability in nearly all of this region. If it falls in Region 3, then SEDAPAL could achieve reliability with the 75% Budget portfolio.

This would mean implementing four remaining projects: Chancay GW, Chancay Res/Huaral WTP, Lima Sur Desal, and Jacaybamba Res. If it falls in Region 4, then SEDAPAL should implement the projects needed in the 75% Budget portfolio. This will increase deliveries but will not be enough to ensure water reliability. Consequently, SEDAPAL will need to develop additional options—perhaps efficiency, non-traditional water supplies, and demand management measures—to achieve water reliability in these futures. Region 4 represents the remaining vulnerability for SEDAPAL's Master Plan and related projects.

Figure 7-3: A decision tree for robust, adaptive implementation of the Master Plan
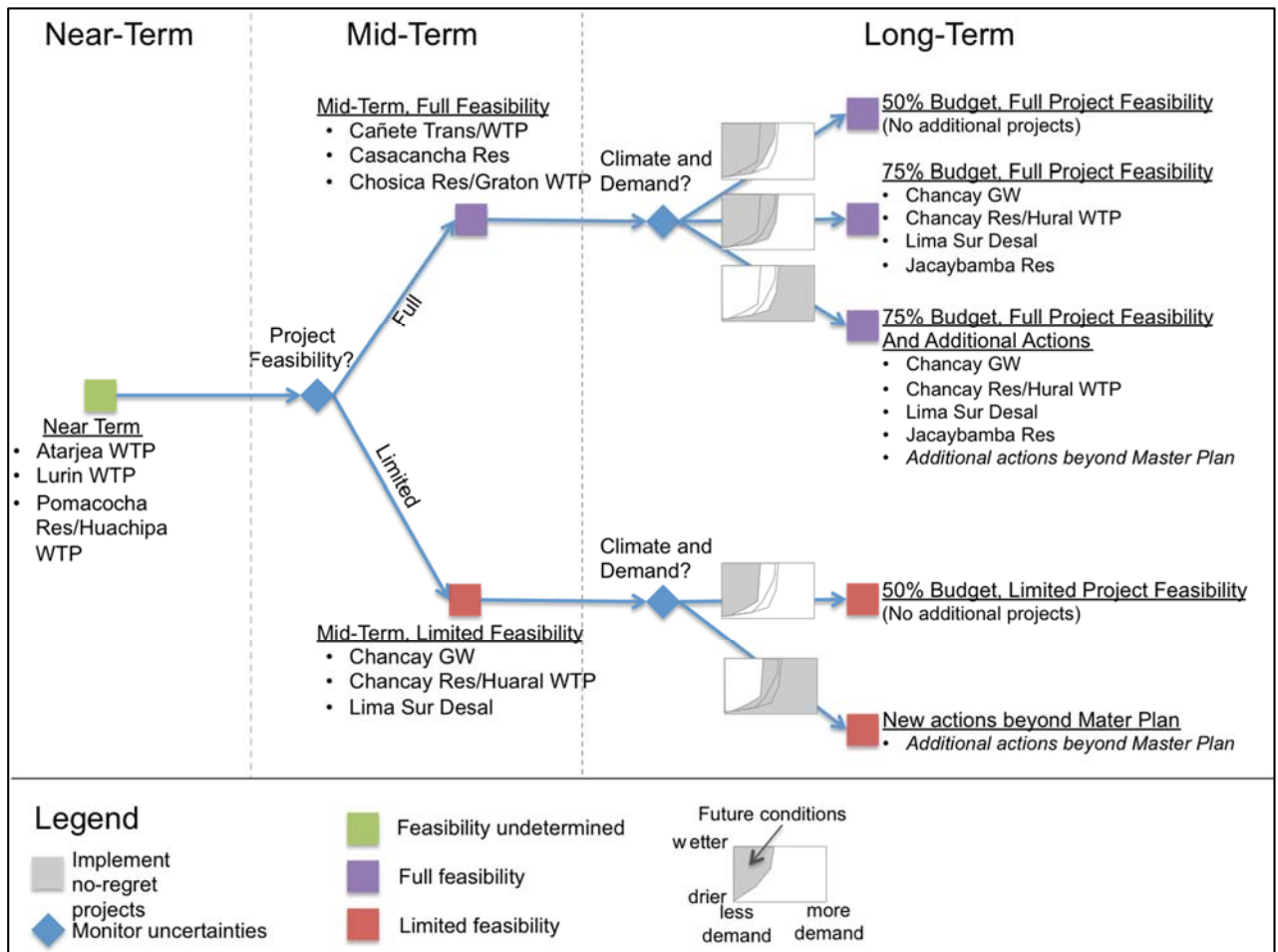
If the more difficult projects are not feasible, following the lower branch of the decision tree, SEDAPAL should implement three different projects in the medium term: Chancay GW, Chancay Res/Huaral WTP, and Lima Sur Desal. At this point, SEDAPAL would have implemented the 50% Budget, Limited Project Feasibility portfolio. Subsequently, if future streamflow and demand fall in Region 1, then it is likely that no further action would be necessary since the 50% Budget, Limited Project Feasibility portfolio achieves water reliability in nearly all of this region. However, this region just extends to SEDAPAL's projection of future demand, and many sources suggest demand

may exceed this. Therefore, it is very possible that the future may fall outside of Region 1. In this case, SEDAPAL will need to develop additional options to achieve water reliability because the 75% and 100% budgets with limited project feasibility do not confer additional benefit. The uncertainty range outside Region 1 represents the remaining vulnerability for SEDAPAL's Master Plan and related projects if Cañete Trans/WTP and Chosica Res/Graton Tunnel are not possible.

This sequence of actions is the most robust way for SEDAPAL to implement its Master Plan and related projects when future demand, streamflow, and project feasibility are deeply uncertain.

8 Discussion and Conclusions

SEDAPAL, Lima's water utility, has developed an aggressive US $2.7 billion Master Plan to improve long-term water reliability in the face of climate change and growing demand. This study draws upon state-of-the-art methods for decision making under deep uncertainty (DMU) to help SEDAPAL implement its Master Plan and related projects robustly, using an adaptive strategy of no-regret options.

8.1 Key Analytical Findings and Recommendations for SEDAPAL

This analysis helps answer several pressing questions about SEDAPAL's Master Plan. First, is the Master Plan sufficient to ensure reliability in the face of deeply uncertain future climate change and demand? The analysis shows that the Master Plan and related investments can ensure reliability in many futures, including to levels of demand that SEDAPAL forecasts, provided that climate change or other drivers do not decrease streamflow significantly. However, it cannot ensure reliability in many plausible futures where demand is higher than projected, streamflow declines, or implementation of critical projects is not possible or delayed.

On the other hand, are all proposed projects necessary to achieving reliability? The analysis shows that SEDAPAL can achieve the very same degree of water reliability more efficiently by implementing only ten of the fourteen projects. This results in a 25% cost savings. In more slightly favorable demand and streamflow conditions, a set of six projects costing 50% of the full budget can achieve reliability.

Many projects are challenging to implement—how should considerations of project feasibility shape the city's investment strategy? SEDAPAL identified three projects that may be more challenging to implement than the others. Our analysis shows that two of these three projects are critical to ensuring long-term water reliability. Without them, SEDAPAL may only be able to achieve reliability if future demand is less than projected, unless climate change very significantly increases streamflow. Therefore, early efforts to ensure timely implementation of these difficult projects are warranted.

Ultimately, how should projects be prioritized? Which should be implemented now, which can be delayed until they are necessary, and what specific indicators would trigger their implementation? We have developed decision tree for SEDAPAL Master Plan implementation, as shown in Figure 7-3. It consists of a set of near-term, no-regret

investments that SEDAPAL can embark upon now; signposts of specific project feasibility, streamflow, and demand conditions SEDAPAL should monitor in the medium and long term; and sets of deferred projects that SEDAPAL should implement if the signposts are triggered. Framed in this way, the decision tree describes steps that can help SEDAPAL implement its Master Plan and related projects robustly:

- In the near term, SEDAPAL can embark upon three no-regret projects at a cost of US $794 million: the Atarjea water treatment plant, the Lurin water treatment plant, and the combined Pomacocha reservoir/Huachipa II water treatment plant. These projects are necessary for ensuring water reliability in the future regardless of project feasibility, streamflow, and demand conditions.
- In the midterm, SEDAPAL should take steps to enable the implementation of the Cañete groundwater project and the combination Chosica water treatment plant/Graton tunnel. These two projects are critical for meeting water reliability in many plausible futures but are also more difficult to implement. If they cannot be implemented, SEDAPAL may not be able to ensure water reliability at its projected levels of demand.
- SEDAPAL should implement the remaining projects adaptively, using the decision tree of no-regret, robust projects for guidance.
- Lastly, SEDAPAL should develop strategies that reduce the need for new water supplies, given that the Master Plan and related projects cannot ensure reliability under all plausible futures. Potential actions include demand management, increasing system efficiency and reducing losses, and developing non-traditional water sources such as reuse of treated wastewater for non-potable purposes (landscape, irrigation, commercial and industrial needs).

8.2 A Follow-On Analysis Could Help SEDAPAL Develop An Integrated Portfolio With Nearer Term Priorities

This project analyzes 14 traditional supply-side infrastructure investment projects for SEDAPAL. It reveals that supply-side investments alone are not enough and that efficiency, demand management, and non-traditional water supply projects may be necessary for robustly achieving long-term water reliability. In some cases, such investments may be more economically efficient than the proposed infrastructure-intensive projects, may serve different regions of Lima that are otherwise underserved, or may offer additional flexibility if they have short lead-times and can be implemented quickly as needed. SEDAPAL recently submitted a collection of such projects to SUNASS, Lima's water supply and sanitation regulatory authority.

A subsequent analysis of investments based on the methodology used in this work would help SEDAPAL prioritize among those investments as well. This would produce an integrated and efficient portfolio of traditional and non-traditional water supplies, efficiency measures, and demand management actions. Among its benefits, an integrated strategy offers more flexibility and responsiveness in the face of uncertainty.

This project focuses on water reliability by 2040, the horizon of SEDAPAL's Master Plan. Yet SEDAPAL's water reliability in the nearer term is also uncertain—the city is

growing fast and changing rapidly. Simultaneously, some projects may take many years to implement; others may take decades. It would be useful to prioritize further the no-regret projects based on their impact on nearer-term water reliability and their implementation timeframes. This would help SEDAPAL achieve near-term water reliability goals and determine with greater precision when it must begin implementing each project to ensure it will be ready to supply water when it is needed.

8.3 SEDAPAL Could Use DMU Approaches In Other Planning Efforts

The future may bring severe multi-year droughts to Lima such as those experienced in other parts of the world. SEDAPAL could use DMU methodologies to update its multi-year drought management plan to complement its Master Plan implementation strategy, but with a focus on shorter-term actions. Such a drought management plan would involve a mix of short-term actions (such as water restrictions and using tailored operating rules for reservoirs and other infrastructure), mid-term actions (such as water banking and encouraging efficient end-use technologies), and long-term actions such as those assessed in this study. It would also involve a mix of near-term uncertainties (such as drought length, severity, and adoption of policies) as well as long-term uncertainties (such as climate change and demand).

Water reliability is intimately linked with water quality, as water pollution can limit the amount of water available for drinking, agriculture, and other uses. Lima's water supply is vulnerable to a variety of pollution sources—upstream agricultural runoff, urban runoff, mining, and the waste streams of many different industries. This analysis highlights projects and water sources that are critical for water reliability, thus indicating where water quality is also of highest importance. Using the water quality functionalities built in to WEAP, or coupling water quality models to WEAP, SEDAPAL could expand this study to consider water quality issues. Specifically, SEDAPAL could use DMU methods to further understand what activities most threaten water quality and where, and develop a strategy of investment projects, operation rules, and regulatory policies that would help reduce pollution and mitigate the effects of pollution. Such a strategy could form the basis for collaboration with industry, regulators, and stakeholders concerned with water quality.

8.4 Lessons Learned

RDM and related DMU methods represent a new way of thinking about how near-term actions can best manage future risks. Analysts are generally trained in predictive thinking and the decision makers they inform often expect predictive quantitative information. DMU methods answer a fundamentally different question. Rather than ask, "what will happen?" they allows analysts and decision makers to ask, "What should we do today to most effectively manage the full range of events that might happen?" This project holds two key lessons for future applications of DMU, which we discuss in turn.

8.4.1 The Value of Methodological Impartiality and Flexibility

In our experience, analysts (including consultants and researchers from academia) approach a problem with a particular methodology and set of techniques in mind from the outset. It is often the one in which they are most skilled, whether it be benefit-cost analysis, scenario planning, or a particular DMU method. Many requests for project analyses (e.g., requests for proposals) encourage this implicitly by asking analysts to articulate a detailed technical approach to a problem based on just a short description and before meeting stakeholders.

This way of thinking can be limiting both for the project and for the analysts undertaking it. It can implicitly and explicitly limit analysts' opportunity to draw upon the best methodology or methodologies for the problem, and hamper the evolution of the methodological approach as the project proceeds. The implicit limitation arises because little time and few resources are built into the project to experiment with methodologies and techniques. The explicit limitation arises because progress is often benchmarked against a scope of work that details a methodological approach that was developed before the project began. The result is that analysts may not draw upon the methods that are best suited to a problem.

This project had few preconceived expectations and restrictions, and we believe this contributed significantly to our being able to draw upon multiple methodologies and evolve the approach as the project went on. While we, too, began with the intent of using a particular approach (Robust Decision Making), we found mid-course that incorporating thinking from Decision Scaling, Adaptive Pathways, and interactive, adaptive decision support would serve SEDAPAL better than our original methodological framing alone. The flexibility and exploratory nature of this project allowed us to adapt to the changing needs of the project. Moreover, these changing needs became clear from an evolution in thinking on the parts of both the analytical team and SEDAPAL, as the former better understood the planning problem and the latter better understood the power of DMU methods. We urge future projects and analyses to embrace this approach still further by being more agnostic to the specific DMU technique, embedding methodological exploration and development into the project budget and timeline, and seeking opportunities for drawing upon multiple methodologies.

8.4.2 The Value of Participatory Analysis and the Stakeholder's Commitment to Innovation

In many projects, technical teams of external consultants and researchers perform an analysis for a client or stakeholder (i.e., SEDAPAL). The technical team produces analysis and findings and the stakeholder receives them. This allocation of roles runs the risk that the analysis will not truly meet stakeholders' needs, as the literature on decision support notes (National Research Council, 2009). The analysis may not answer the questions that the stakeholder is asking; the stakeholder may not buy into the methodological process or findings; or the stakeholder may not be able to take intellectual ownership of methodology, tools, and outcomes.

SEDAPAL committed to this project and to the process of "deliberation with analysis" that is recognized as best practices for climate-related decision making

(National Research Council, 2009). First, it committed its technical staff to be a core part of the analytical team. They brought their expertise on Lima's water needs and resources, SEDAPAL's system, the regulatory and policy context in which they make decisions, and an understanding of the goals and aims of their Master Plan. The analytical team met weekly – sometimes daily – by phone. SEDAPAL's staff validated the data, models, and findings at each step of the analysis. Their involvement has ensured that the analysis asks and answers the right questions, that the results are important and practical for SEDAPAL, and that SEDAPAL seeks to take ownership of the methods and tools developed in the analysis and employ them in their future planning activities.

Second, and perhaps even more importantly, SEDAPAL was willing to experiment with a new approach to long-term planning and embark on a complex analysis that differed greatly from approaches it used in the past. In embracing innovation, SEDAPAL also embraced the possibility that the analysis would produce complex or controversial findings that it would have to explain to stakeholders, including regulators and national authorities. Because of SEDAPAL's boldness, we were able to ask and answer difficult questions about its Master Plan in the pursuit of long-term water reliability for Lima.

8.5 Conclusions

This project helps SEDAPAL understand its Master Plan more fully. It enables SEDAPAL to assess climate change threats without first needing to predict the future climate. It helps SEDAPAL identify projects that are particularly important for achieving water reliability. And, it reveals the strengths and vulnerabilities of its Master Plan concisely—as a specific set of conditions in which the Master Plan and related projects can achieve water reliability and in which additional actions may be necessary. It also helps SEDAPAL implement its Master Plan robustly by identifying near-term, no-regret projects that it can embark upon now, while pursuing additional actions adaptively as future conditions evolve.

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Appendix A. Creating Demand and Streamflow Futures

We statistically generated 300 demand and streamflow futures, in addition to a future representing no change from today (855 Mm3 of demand and historical streamflows). A future is defined by a specific combination of values, one for each of the uncertainties. These futures are not predictions, and we do not assign any likelihood to their occurrence. Rather, we use them to stress test and better understand the behavior of the Master Plan. Using WEAP, we determined the 90th percentile of monthly met demand of each individual project and of the portfolios in each of these 300 futures.

In this analysis, to create the 300 futures we use Latin Hypercube Sampling (LHS). LHS is a randomized experimental design based on the higher dimensional generalization of a Latin Square. Our experience suggests LHC is more useful for multi-scenario analyses than other standard sampling methods, such Monte Carlo or full-factorial, because it provides the most complete exploration of the model's behavior over the input space for the fewest number of points in sample (Saltelli et al, 2000; Groves et al., 2014). To generate the futures, LHS

1. Takes as input the minimum and maximum values for each of the u uncertainties and the number n of futures desired,
2. Divides each uncertainty range into n values at equally spaced intervals, and
3. Randomly generates n futures such that each of the n values for an uncertainty is included in exactly one future, and no future contains more than one value from the nth interval.

To create these futures, we first need to identify appropriate ranges for the demand and streamflow uncertainties considered. We discuss these in turn.

Generating Demand Futures

We used four sources of data of population and water use projections for the Lima Metropolitan Region: two from SEDAPAL (SEDAPAL, 2014),[11] one from Peru's National Institute of Statistics and Informatics (INEA[12]), and one from a study by the German Federal Enterprise for International Cooperation for SEDAPAL. Each source projected (i) the total population in Lima in 2040 and (ii) demand per capita, which includes system losses. We multiplied each demand per capita projection by each population projection, as illustrated in Table A-1. We defined the ranges by multiplying the minimum and maximum population projections with the minimum and maximum demand per capita, respectively. From this method, the estimated minimum and maximum are 730 Mm3 and 1790 Mm3, respectively (red values in Table A-1). For each of the 300 futures, we assume that the ratio of regional demand to total demand remained

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[11] Personal communication with SEDAPAL, January 2014.

[12] http://www.inei.gob.pe/

constant. We also assume that demand remains constant throughout the year and therefore divide annual demand into twelve roughly equal monthly demands.[13]

Table A-1:Ranges for plausible demand futures (m3/year), Total Lima, 2040

			Population			
			SEDAPAL	5-Year Plan	INEI	GIZ
		x	*12.5M*	*13.3M*	*11.7M*	*17.3M*
Water Consumption (m3/p/year)	SEDAPAL	*83*	1,031M	1,101M	966M	1,425M
	5-Year Plan	*84*	1,049M	1,120M	982M	1,450M
	INEI	*63*	787M	840M	**737M**	1,088M
	GIZ - high	*102*	1,282M	1,370M	1,201M	**1,773M**

Generating Streamflow Futures

In contrast to demand, there is significant variation in intra-annual streamflow due to seasonal variation in precipitation at the headwaters of each of these basins in the Andes (Vera *et al.*, 2006). Because of its extensive reservoir storage capacity, however, the system is largely insensitive to month-to-month changes in streamflow and much more sensitive to changes in seasonal in streamflow. Therefore, we represent each streamflow future with two values, one for the dry season (March-November) and one for the wet season (December-February).

Our method of estimating future streamflow is to use a delta change factor to adjust historical monthly flows, consistent with the principles of Decision Scaling (Brown, 2011). Under this method, we apply a range of percent changes to historical precipitation data to obtain projections of future precipitation. The precipitation data is then used in a rainfall-runoff model to estimate future streamflow.

We specify the range of delta factors to exceed that from downscaled climate projections. We use estimates of downscaled precipitation changes from global climate models and historical streamflow data from SEDAPAL. Figure 4-1 summarizes the changes in annual and seasonal precipitation projected by 15 climate models in 3 emissions scenarios. We use the minimum and maximum changes as the ranges for an LHS-generated set of monthly precipitation deltas. That is, each of the 300 futures contains 12 unique values of monthly change factors. Without a rainfall-runoff model, we

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[13] In many parts of the world, variations in temperature and precipitation within a year drive intra-annual variations in demand. Demand increases in hotter or drier periods and decreases in cooler or wetter periods. Lima has little variation in intra-annual demand because temperature is roughly constant throughout the year and precipitation is negligible. This is consistent with SEDAPAL's observations of historical demand.

assume a 1:1 relationship between precipitation and runoff and apply these change factors directly to the 45-year monthly historical streamflow record. This results in 300 different sequences of 540 months of streamflow. We use these months of streamflow to emulate interannual variability at a single point in time, and not as a transient sequence of streamflow across time. That is, we treat all 540 months of data as samples from a single future climate regime in 2040, not as a 45-year sequence of streamflow from 2015 to 2060.

Assessing Project And Portfolio Performance With Futures

We run each project and portfolio in 300 futures to test its performance under different uncertain demand and streamflow conditions. To evaluate a project or portfolio in a single future, WEAP calculates the monthly met demand as a percent of total demand in each of the 540 months. We post process these results to calculate our key metric—the 90th percentile of monthly met demand across the 540 months.

A key objective of the analysis is to summarize the conditions under which a portfolio achieves water reliability. While there are three exogenous demand and streamflow variables in each future, we describe performance in terms of demand and dry season streamflow because the system as currently envisioned is sensitive to changes in dry season streamflow but not wet season streamflow. This is because, in the wet season, SEDAPAL prioritizes filling of reservoirs to meet upcoming dry season demand, and streamflow in the wet season often exceeds reservoir capacity. Therefore most changes in wet-season streamflow do not affect water deliveries. In contrast, in the dry season, changes in streamflow can have immediate and direct impact on water deliveries and met demand. Changes in how SEDAPAL operates its system could change this sensitivity.