WATER GLOBAL PRACTICE

Preparing for Future Droughts in Lima, Peru

Enhancing Lima's Drought Management Plan to Meet Future Challenges

MAY 2019

David G. Groves, Laura Bonzanigo,
James Syme, Nathan Engle,
and Ivan Rodriguez

WORLD BANK GROUP

About the Water Global Practice

Launched in 2014, the World Bank Group's Water Global Practice brings together financing, knowledge, and implementation in one platform. By combining the Bank's global knowledge with country investments, this model generates more firepower for transformational solutions to help countries grow sustainably.

Please visit us at www.worldbank.org/water or follow us on Twitter at @WorldBankWater.

About GWSP

This publication received the support of the Global Water Security & Sanitation Partnership (GWSP). GWSP is a multidonor trust fund administered by the World Bank's Water Global Practice and supported by Australia's Department of Foreign Affairs and Trade; the Bill & Melinda Gates Foundation; The Netherlands' Ministry of Foreign Trade and Development Cooperation; Norway's Ministry of Foreign Affairs; the Rockefeller Foundation; the Swedish International Development Cooperation Agency; Switzerland's State Secretariat for Economic Affairs; the Swiss Agency for Development and Cooperation; Irish Aid; and the U.K. Department for International Development.

Please visit us at www.worldbank.org/gwsp or follow us on Twitter #gwsp.

Preparing for Future Droughts in Lima, Peru

Enhancing Lima's Drought Management Plan to Meet Future Challenges

MAY 2019

David G. Groves, Laura Bonzanigo, James Syme,
Nathan L. Engle, and Ivàn Rodriguez Cabanillas

WORLD BANK GROUP

1818 H Street NW, Washington, DC 20433

Telephone: 202-473-1000; Internet: www.worldbank.org

Cover photo: Geraint Rowland.

Cover design: Jean Franz, Franz & Company, Inc.

Contents

Box

Maps

Figures

Tables

Acknowledgments

This activity is the second output of a 4-year long collaboration between SEDAPAL's technical teams and World Bank teams, working on mainstreaming Decision Making Under Uncertainty methodologies in client countries. The first collaboration entailed the evaluation of a large investment plan for improving their system via additional storage and treatment capacity and resulted in the robust prioritization of the individual investments (Kalra et al. 2015). The task team leader and authors thank the many people who have made this project possible and contributed to its success. These include Yolanda Andia Cardenas, Michael Vega Baltodano, Arturo Parra Quispe, Josué Cespedes Alarcon (from SEDAPAL); Juliana Garrido, Habab Taifour, Sanjay Pahuja, Amal Talbi, Marisol Gisel Noriega Ramos, Iris Marmanillo (from the World Bank); Nidhi Kalra (RAND), Cayo Ramos (University La Molina), and Marieke Goettsch (Inter-American Development Bank). Financial support from the Korean Green Growth Trust Fund is gratefully acknowledged.

Summary

Background

Lima is the capital of and largest city in Peru, with an estimated population of about 10 million people. SEDAPAL, Lima's water utility, provides water to most of the metropolitan region. While SEDAPAL is generally able to meet the current needs of its customers and respond effectively to most drought conditions that have been experienced in the past, it faces a number of challenges doing so in the future. A rapidly growing population and expanding city will likely increase demand. Currently available surface and groundwater supplies that SEDAPAL relies on are also just adequate to meet current needs. Changes in these supplies—either long-lasting reductions or variability in supply due to climate change, or more acute or frequent droughts—would challenge SEDAPAL's ability to manage drought conditions.

Recognizing the urgency of Lima's water situation, in 2013 SEDAPAL developed an aggressive $2.3 billion Master Plan for the years 2015-44 to augment their supply. While the investments identified in the plan will help preserve SEDAPAL's capability for addressing increasing demand in the future, it did not specifically consider the ability for SEDAPAL to successfully manage future droughts. A previous collaboration between the World Bank and SEDAPAL in 2014-15 evaluated the robustness[1] of SEDAPAL's Master Plan. This previous study focused on long term trends of climate and demand and focused only on the infrastructure investments for increasing supply identified in the Master Plan.

This study builds upon the results of the 2015 study by evaluating the performance of SEDAPAL's current drought management plan against future droughts and proposes augmentations. This study takes a deeper look into the operation of the system, the different triggers, and other possible augmentations than those related to increasing supply. The audience of this report includes SEDAPAL and stakeholders from Lima as well as other water managers and researchers interested in drought management planning methodologies and case studies.

SEDAPAL's current drought management plan includes a set of actions triggered during hydrologically dry periods. We used a model of SEDAPAL's management system to evaluate how the current drought management plan would perform across a wide range of plausible hydrologic conditions and current and increasing demands. To do so, we developed hundreds of different futures reflecting different assumptions about how the intensity and frequency of dry and wet conditions might change over the coming decades. We then simulated the performance of the current and enhanced SEDAPAL system under these different futures.

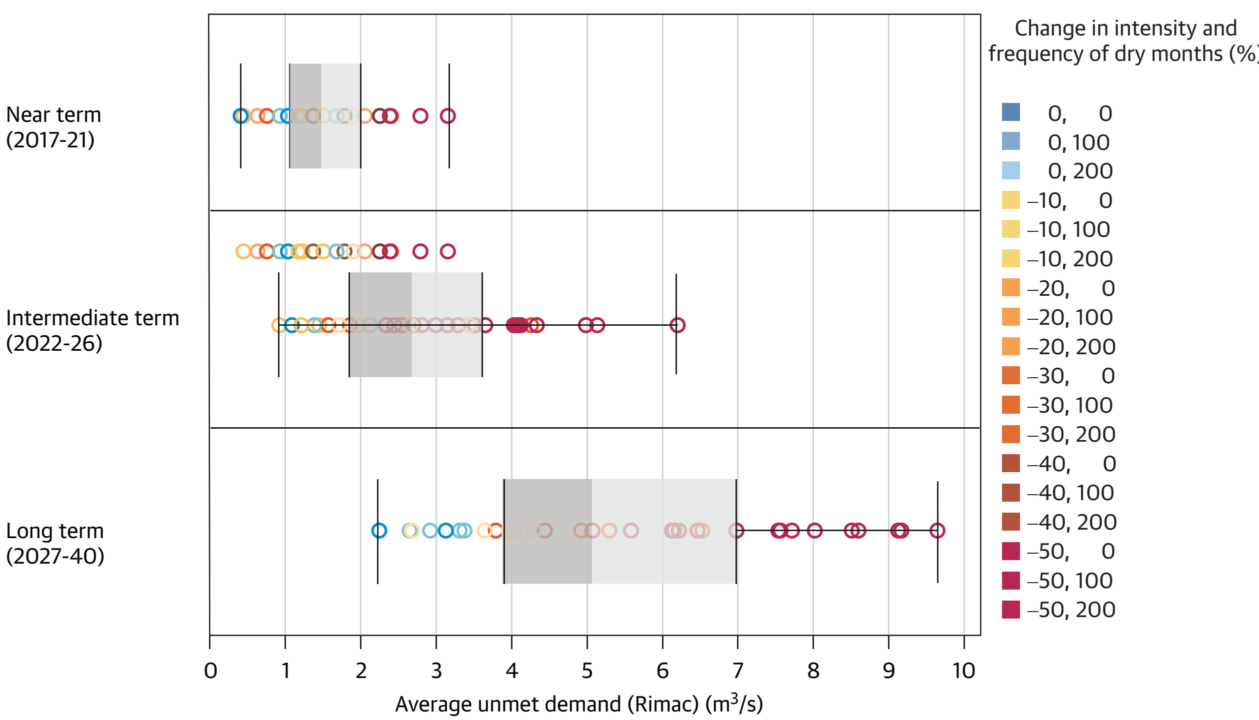
This study is novel, as it uses a methodology called Decision Making under Deep Uncertainty to explore uncertainty in near-term drought management conditions and to identify drought management strategies robust to these uncertainties. The approach is participatory and iterative, and we worked closely with SEDAPAL planners and operational teams to develop a suitable systems model of the SEDAPAL system, define useful plausible futures, performance metrics, and infrastructure and drought management strategies.

Results

The simulations show that the current drought management plan can successfully mitigate recent drought conditions under today's system and level of demand. The current drought management plan would also perform reasonably well in the near-term future under moderate droughts (such as the ones in 1980 and 2004). Without additional storage system improvements, however, the current drought management plan would perform less well under increasing demands.[2]

Future hydrologic variability is uncertain, and if the intensity and frequency of dry periods increases, larger unmet demands during dry periods would result. More intense wet periods do not compensate for these drier conditions, but more frequent wet periods partially do. Figure S.1 shows the range of unmet demand during dry months in the near term, intermediate term, and long term, for hundreds of different futures, reflecting plausible drought conditions. Each circle in the plot represents one future and is colored by the assumed change in intensity and frequency for dry months. The figure shows that under the assumption that the intensity and frequency of dry periods remain the same, average unmet demand increases from less than 0.5 m^3/s in the near term to a bit over 1.5 m^3/s by the long term time period (dark blue results). However, if droughts

FIGURE S.1. Distribution of Unmet Demand Averaged over Dry and Normal/Wet Years across Different Hydrologic Sequences for Different Time Periods for the Current System and Drought Management



Note: In the box plots, the middle gray box represents the middle 50 percent of scores for the scenarios; the dark gray indicates the second quartile; and the light gray indicates the third quartile.

became more extreme, unmet demand could increase to as much as 3 m^3/s in the near term; over 5 m^3/s in the intermediate term; and almost 9 m^3/s in the long term. As a reference, today's demand is approximately 20-22 m^3/s.

The study evaluates the impact of near-term system improvements and investments from the Master Plan that are already underway (Phase 1), specifically the Autisha, Casacancha, and Jacaybamba Reservoirs, the expansion of the Atarjea water treatment plant (WTP), and efficiency improvements and loss reduction investments. It also evaluates the impact of the proposed long term (Phase 2) system improvements from the Master Plan to the Marca II and Huachipa WTPs. The analysis shows that these projects play an important role in improving SEDAPAL's ability to manage droughts across the wide range of futures. Specifically, enacting the Phase 1 Implementation Plan elements helps slightly in the near term, and more so in the longer term when demands are higher. Developing Phase 2 storage improves SEDAPAL's drought management plan performance even more but is expensive and potentially contentious.[3]

The vulnerability analysis next looked more systematically across the uncertainties and characterized the robustness of the system by the average unmet demand across specific time periods. Robustness Level 1 indicates that on average unmet demand would not exceed 1 m^3/s, which roughly approximates the expected performance of SEDAPAL's current system should there be a repeat of recent drought conditions (0.66 m^3/s average unmet demand during a dry year). Robustness Level 2 indicates that on average 2 m^3/s of unmet demand would result. Larger robustness levels indicate less robustness. Figure S.2 shows one example of a robustness map under the current system, plus Phase 1 improvements and current drought management in the long term. In this figure, the robustness level is shown for each future, where the columns indicate changes in wet year frequency and intensity and the rows indicate changes in dry year frequency and intensity changes. The figure shows that even when activating the current drought management actions (under the current system), dry conditions would lead to less robustness (higher robustness levels), ranging from 2 m^3/s for small changes (such as 10 percent drier dry months) to greater than 5 m^3/s for conditions in which dry month intensity is 50 percent drier; or less than 50 percent if coupled with an increased frequency of dry months. Note that increasing the frequency of wet months does not compensate for an increase in dry month frequency.

The current drought management plan can be improved and lead to reduced future vulnerability through the implementation of additional actions. We investigated what would happen during droughts if, in addition to the current drought management actions, emergency conservation measures were added, reservoir operations were modified, and new drought storage was made available. Figure S.3 summarizes the specific drought management actions included in five different strategies that were evaluated by this study.

We found that once Phase 1 improvements come online, implementing additional drought demand management actions helps to increase robustness to the 1 m^3/s level for more possible

FIGURE S.2. Long Term (2027-40) Robustness Map under the Current Drought Management System, with Phase 1 Improvements

Note: Under the current system and current drought management, robustness level 1 is never achieved in the long term, not even without any changes in hydrological droughts.

FIGURE S.3. Drought Management Strategies

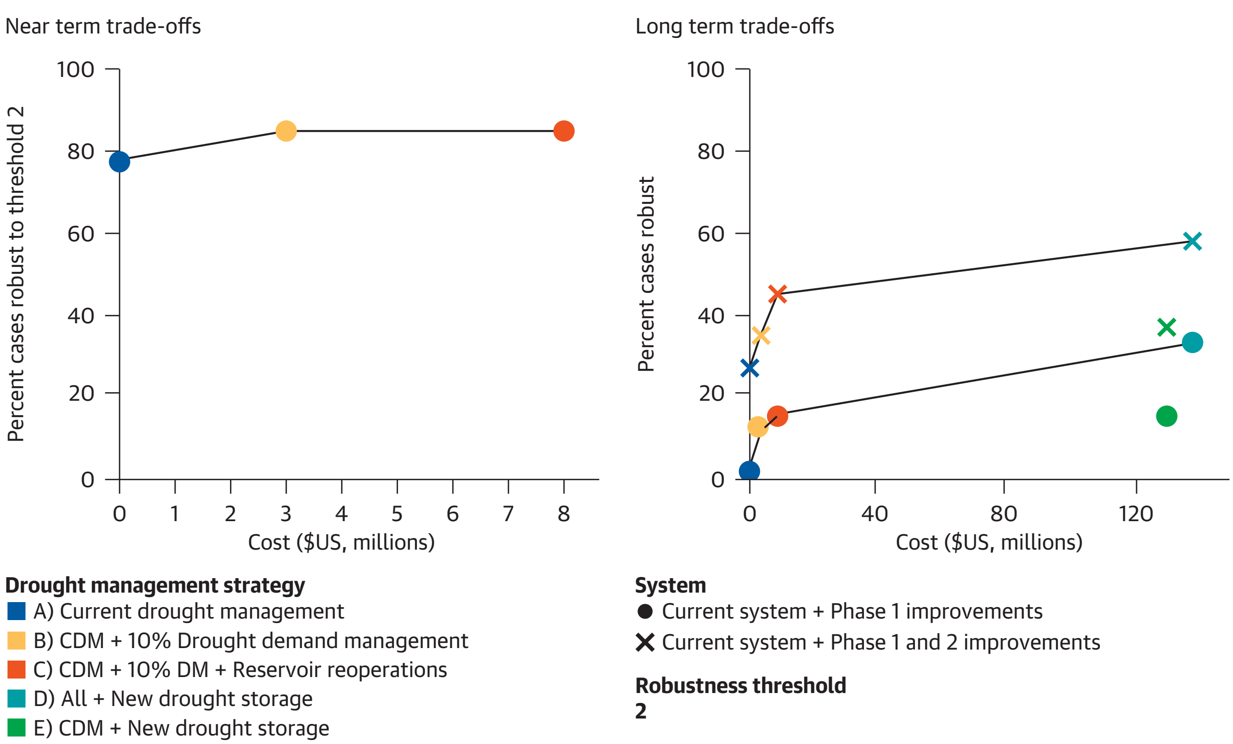
	Current drought management	Emergency 10% reduction in demand	Alternative reservoir operations	New drought reservoirs
A) Current drought management (CDM)	✓			
B) Add drought conservation (CDM + DC)	✓	✓		
C) Add reservoir reoperations (CDM + DC + Reop)	✓	✓	✓	
D) Add drought reservoirs (CDM + DC + Reop + Res)	✓	✓	✓	✓
E) Add drought reservoirs only (CDM + Res)	✓			✓

future scenarios. There is also only slight improvement in near-term robustness by reoperating the reservoirs. In the long term, particularly if in conjunction with Phase 2 improvements (i.e., Marca II/Huachipa WTPs), the activation of emergency demand control and reoperation of the system (Strategy C) makes it robust to the 1 m³/s threshold under current climate conditions and even under hydrologies through a 20 percent drying. As SEDAPAL builds Phase 1 and 2 investments and adds additional drought storage, the system becomes robust to a 2 m^3/s threshold up until a doubling of dry months frequency and a 20 percent drying.

While the robustness analysis suggests the implementation of all options (Strategy D), they are not without cost, and SEDAPAL must coordinate with other entities to implement these improvements. In particular, the new drought reservoirs would cost $129 million and require intense coordination with the electricity company ENEL, the governmental regulator SUNASS, and other public entities like the National Water Authority (ANA). Figure S.4 shows the key trade-offs for the drought management strategies in terms of the percentage of cases that are robust to the 2 m^3/s threshold (vertical axes) and cost (horizontal axes) in the near term (left panel) and long term (right panel). The left panel shows that in the near term Strategy C (red symbol) does not provide additional robustness, yet it incurs additional cost. However, in the long term this strategy yields measurable robustness improvements, particularly if the Phase 2 infrastructure improvements are included (red x symbol). Figure S.4 also shows the additional benefit that comes with Strategy D, although at a high cost.

Based on these findings, we propose an adaptive implementation approach for augmenting additional drought management actions. In the near and intermediate term, implementing the 10 percent drought demand management policy (B) in conjunction with the Phase 1

FIGURE S.4. Consolidated Robustness and Cost Trade-Offs in the Near Term (2017-21) and Long Term (2027-40)

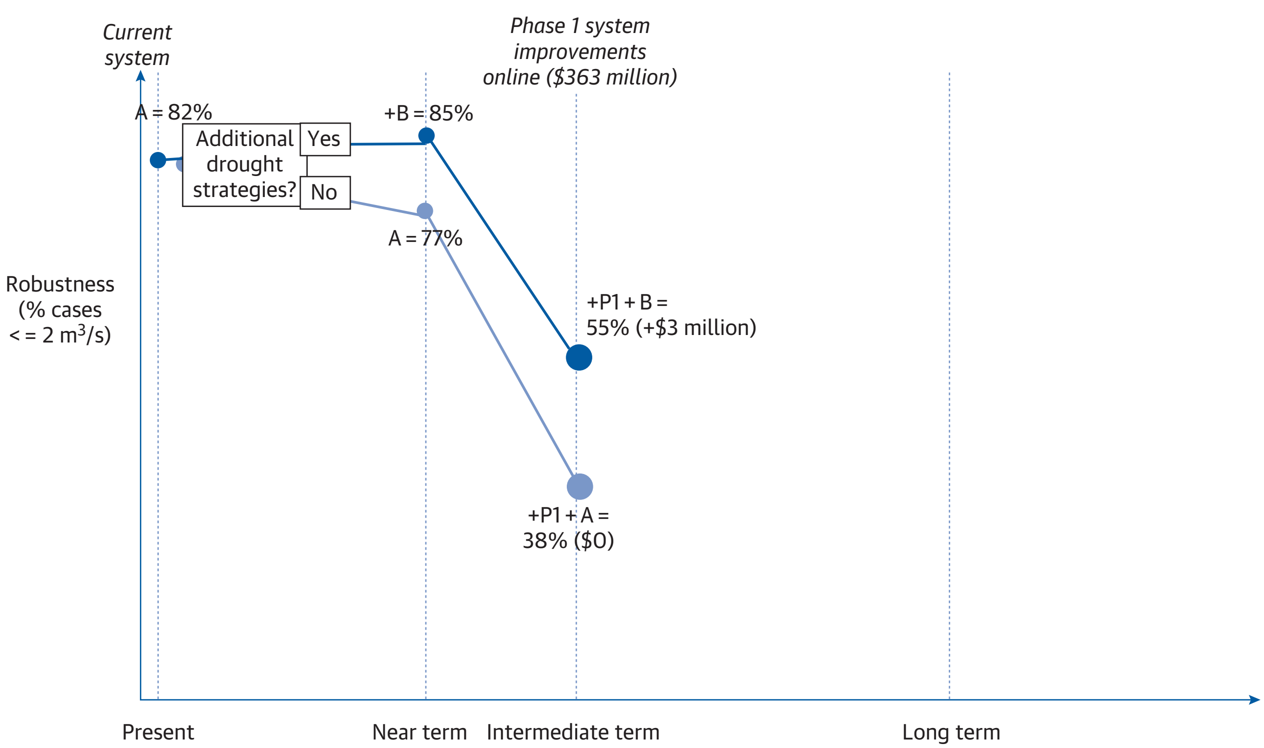


Note: These results for both the near-term and long-term trade-offs are based on a robustnes threshold of 2 m^3/s . We used a decision support tool via Tableau Public's visualization software, which can be accessed at https://tinyurl.com/ya57valf. The user of the decision support tool can choose other thresholds as well. Note that in the future, with higher demand, the same threshold would be more stringent/ambitious.

system improvements will help achieve moderate robustness at a low cost. Specifically, they will achieve robustness to the 2 m^3/s threshold under 80 percent of drought scenarios explored at an additional investment of $3 million. This leaves SEDAPAL vulnerable to hydrologies in which dry periods are 40 percent drier and 3 times more frequent, and the tested operational changes do not provide additional improvement (figure S.5).

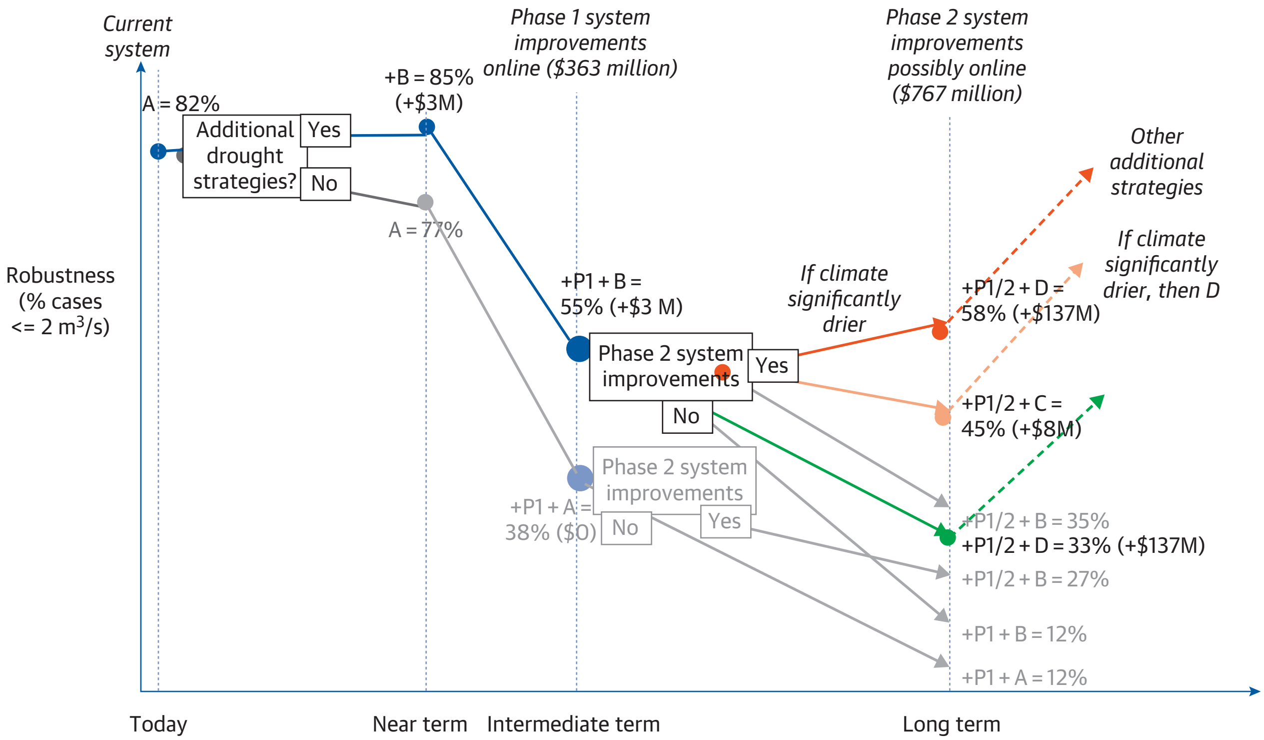
In the long term, introducing the tested operational changes (Strategy C), with their low cost and modest coordination requirements, results in some significant robustness benefits. The need for additional drought storage, which incurs significant costs and levels of coordination, depends on whether the Phase 2 system improvements are implemented and how much more intense and frequent dry periods are in the future. If hydrological conditions tend toward more significant drying, and particularly if Phase 2 is not implemented, then these drought-specific infrastructure improvements become seemingly more justified. However, Phase 2, with its large added storage and treatment capacity, will help increase robustness levels, leaving the system vulnerable only to two scenarios: if dry months are three times more frequent and 20 percent drier, or if dry months are 30 percent drier, regardless of frequency. SEDAPAL should consider planning for higher levels of robustness in the long term, while monitoring conditions in the near future. Figure S.6 shows that the highest level of robustness to the 2 m^3/s threshold that can be achieved with both Phase 1 and Phase 2 system

FIGURE S.5. Phased Implementation Plan and Qualitative Robustness Trends in the Near Term (2017-21) and Intermediate Term (2022-26), Including Cost (without Phase 2 System Improvements)



Note: A = Scenario A; B = Scenario B; P1 = Phase 1 system improvements.

FIGURE S.6. Recommended Drought Management Augmentation Implementation Plan for SEDAPAL



Note: Possible options the study does not recommend are shown in gray. A = Scenario A; B = Scenario B; C = Scenario C; D = Scenario D; P1 = Phase 1 system improvements; P1/2 = Phase 1 and Phase 2 system improvements.

improvements and drought management strategies is 58 percent. While this may seem low, note that the remaining 42 percent of cases are characterized by more extreme hydrologies, where the frequency of dry months increases by 200 percent and their intensity by more than 30 percent. For these cases, robustness is only achieved under the 3 m³/s threshold.

In conclusion, this study provides a first look at how SEDAPAL's drought management plan could be strengthened over time to accommodate changes in demand and drought conditions. The analysis suggests a clear course of action for SEDAPAL to follow to augment its drought management strategy to accommodate future changes. Specifically, we provide the following steps as a guide for SEDAPAL:

1. Complete the Phase 1 system improvements.
2. In the near term, prepare to implement additional drought conservation measures (Strategy B).
3. Begin evaluation of drought storage for possible implementation in the intermediate term (Strategy D).
4. Continue to evaluate the feasibility of Phase 2 system improvements (i.e. Marca II), and particularly its social and environmental feasibility.

5. Even if Marca II is deemed feasible, evaluate the system operations to best take advantage of existing storage and new storage (Strategy C), and eventually implement the new drought storage (Strategy D).
    a. If Marca II is not deemed feasible, implement Strategy D, remaining aware that the new reservoirs would only compensate for the absence of the the Pomacocha Reservoir during drought years. Therefore, additional system improvements should be considered, either from the SEDAPAL Master Plan, or new solutions, including other system operations.
6. Even if Pomacocha is deemed feasible, explore additional measures to protect SEDAPAL from more extreme droughts. These could include the remaining elements of the Master Plan, but also new investments that SEDAPAL is currently exploring, like green infrastructure or treated wastewater reuse.

Notes

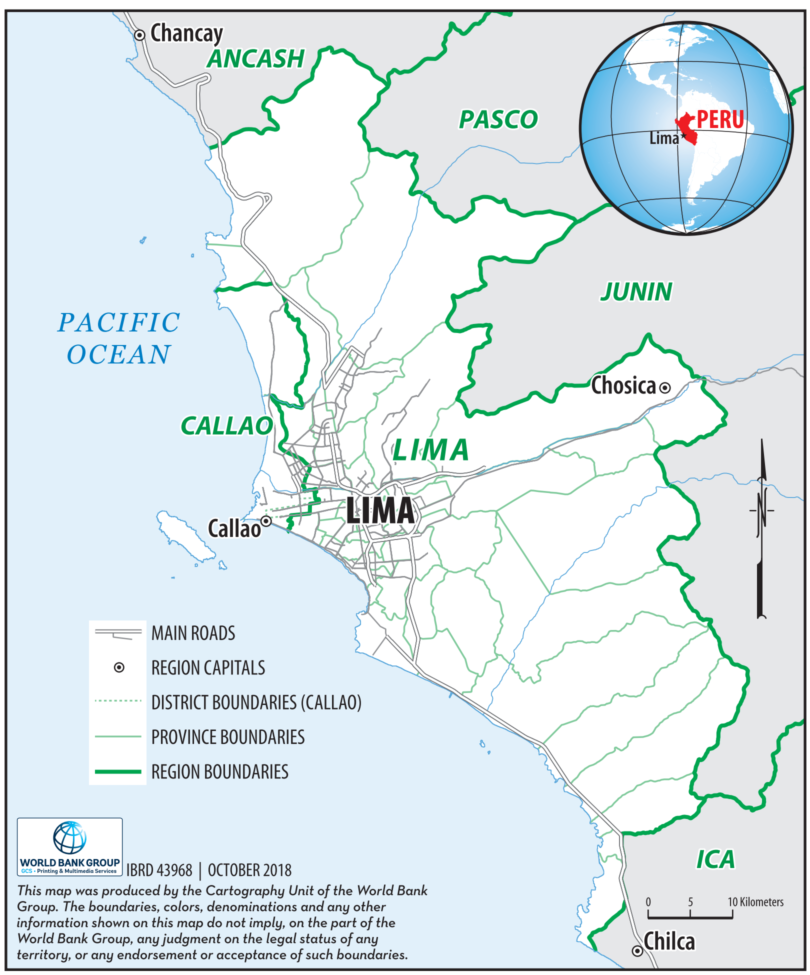
1. We use "robustness" to indicate the range of plausible futures for which a SEDAPAL drought management strategy would not lead to high unmet demand (adapted from Lempert et al. 2003).
2. Marca II includes the large 90 million cubic meters Pomacocha Reservoir on the Amazonian side of the Andes and a trans-Andean tunnel to connect it to the SEDAPAL system. Although the high storage capacity would certainly increase the reliability of SEDAPAL's water supply, the social and environmental impacts of the dam need to be considered further. Moreover, other users in the area already have water concessions, which may significantly reduce the water availability for the dam.

Chapter 1 Introduction

1.1 Lima, Peru, and Its Water Utility, SEDAPAL

Lima is the capital of and largest city in Peru, with an estimated population of about 10 million people.[1] Lima is the second largest desert city in the world, following only Cairo, Egypt in size. While Lima lies on an expansive, dry coastal desert, the peaks of the Andes mountains are located less than 80 kilometers to the east. Approximately 80 percent of the city's drinking water comes from these mountains, primarily via the Rimac River. Natural flows in the Rimac River is highly dependent on mountain precipitation, and there is significant variation in these flows across the seasons (from an average of 20 m^3/s in the dry season to 45 m^3/s in the wet season) and across years.[2] Precipitation in the mountains is characterized by two primary seasons: the wet season, which runs from December to April; and the dry season, which runs from May to November. There are also significant groundwater resources available in Lima. Although the Lima aquifer has an estimated area of 260 km^2 and an average thickness between 400m and 500m, the sustainable yield is uncertain (Montoya and Mamani 2013).

MAP 1.1. Map of Lima, Peru



SEDAPAL, Lima's water utility, provides water to most of the metropolitan region, including the adjacent port district of Callao and its approximately one million people (INEI 2013). SEDAPAL's system provides on average 23 m^3/s to its customers from a mix of surface and groundwater supplies (SEDAPAL 2017). With 15 managed lakes 3 and 4 large reservoirs, it has a storage capacity of 331 million cubic meters. Moreover, the system has 358 groundwater wells, of which 330 are directly managed by SEDAPAL and 28 are privately owned.[4] Lima's water users are distributed across four regions, via a network that stretches more than 14,000 kilometers:

- **Central Lima** (85 percent of demand): supplied mostly by the Rimac River via Lima's major water treatment plant (WTP), Atarjea (18 m^3/s treatment capacity);
- **Eastern Lima** (6 percent of demand): supplied mostly by the Rimac River via the Huachipa plant (5 m^3/s nominal treatment capacity);
- **Northern Lima and Callao** (7 percent of demand): in the Chillón basin and supplied by the Chillón River during the wet season (via a 2.4 m^3/s WTP) and by groundwater in the dry season;
- **Southern Lima** (2 percent of demand): in the Lurin basin and supplied by the Lurin River in the rainy seasons, and from groundwater wells and the Atarjea WTP in the dry season.

BOX 1. How the Rimac System Functions

Description of the Rimac River Basin

The Rimac River Basin is located on the Pacific slope of the Andean Mountains and has an area of 3,398 km^2 (Montoya and Mamani 2013). About two thirds of the basin receives significant rainfall and contributes flow to the Rimac River. Several tributaries to the Rimac River, including the Santa Eulalia River, San Mateo River, and the Blanco River, also originate in the Andes and contribute to downstream flows to Lima. Both San Mateo River and the Santa Eulalia River are managed by SEDAPAL.

The Rimac system receives part of its water from the Atlantic side and part from the Pacific side. This system of lakes and reservoirs, which has a total storage capacity of 331 million cubic meters, is currently used for seasonal regulation of drinking water, irrigation, and energy supply in the Rimac River Basin. On the Atlantic side, Antacoto is the biggest reservoir of the system (120 million cubic meters), followed by the Marcapomacocha system of four lakes and the Huascacocha Reservoir (48 million cubic meters). Their water is transferred to the Rimac system during the dry season, via a 10 kilometer long trans-Andean tunnel built in the 1960s. On the Pacific side, the Santa Eulalia River Basin includes 15 managed lakes, built between 1875 and 1940, with an approximate capacity of 77 million cubic meters. Moreover, the Yuracmayo Reservoir provides storage on the Blanco River.

The Graton Tunnel, built in 1962 and located upstream of the town of San Mateo, was designed to drain water from the Casapalca Mine. It is 11 kilometers long and supplies 4.5 m^3/s to the Rimac system in the dry season.

A significant expansion of storage infrastructure took place in 2000, aimed largely at regulating flows in the Rimac River, starting with the enlargement of Antacoto Reservoir and Canal Marcapomacocha-Cuevas, which increased the water flow during the dry season, as measured at Chosica. Wet season flows between these two periods also increased from 39.9 m^3/s to 47.9 m^3/s, though it is unclear whether this increase is due to a difference in hydrological conditions over the different periods or because of a combination of infrastructure improvements and hydrological conditions.

Regulation of the Rimac River Basin

The Rimac River Basin's reservoirs (including Huascacocha, which is located in another basin) are generally filled during the rainy months of December through April. During the dry months of May through November, they release water for hydropower and water supply purposes. To maintain a buffer for dry wet seasons, or longer dry seasons, SEDAPAL has agreed with ENEL, an electric utility and operator of the reservoirs, to always maintain 130 million cubic meters of stored water at the end of the dry season. As ENEL seeks to maximize hydropower production by drawing down the reservoirs, this effectively establishes how much water is released every season.

Water stored in the Huascacocha Reservoir (built in 2013) is the first to be released due to a contractual agreement between SEDAPAL and a private operator. Water released from the Marcapomacocha Reservoir is then transferred to the Rimac River via the Olmos Trans-Andean Tunnel. Finally, if needed, the Santa Eulalia's 15-lake system further supplements the Rimac system.

Two emergency situations can lead to the release of water stored in reservoirs in the Santa Eulalia Basin: (1) when unregulated flow in the Santa Eulalia plus stored water from Marcapomacocha cannot account for required flows at the Chosica station (23 m^3/s) and (2) if an accident or exogenous event occurs that drastically impacts in the system, such as an obstruction of the Trans-Andean Tunnel. Additional water from the Yuracmayo Reservoir supplement natural flows in the San Mateo River, providing an average flow of 11 m^3/s to the Rimac River.

1.2 Water Management Challenges

While SEDAPAL is generally able to meet the current needs of its customers and respond effectively to most drought conditions that have been experienced in the past, it faces a number of challenges doing so in the future.

A rapidly growing population and expanding city will likely increase demand. SEDAPAL recently projected an increase in total demand from 855 million cubic meters per year to 1,125 million cubic meters per year by 2040 (a 25 percent increase), though a subsequent World Bank report highlighted significant uncertainty about this estimate (Kalra et al. 2015; SEDAPAL 2013).

The recently available surface and groundwater supplies that SEDAPAL relies on are also just adequate to meet current needs. Changes in these supplies–either long-lasting reductions in supply due to climate change or long term variability, or more acute or frequent droughts–would challenge SEDAPAL's ability to meet Lima's needs (Kalra et al. 2015). Further compounding SEDAPAL's challenge is its relatively low level of storage to help bridge dry years and capture unused flows during the wet season. Specifically, Lima has a lower storage capacity than many other Latin American cities, at only 35 m^3 per person. This is much lower than the storage of other cities such as Santiago, Chile (135 m^3 per person), Bogotá, Colombia (123 m^3 per person), and Sao Paolo, Brazil (83 m^3 per person) (SEDAPAL 2012). The current storage capacity and the available pumping capacity can only provide a buffer for one low-rainfall wet season.

Together, these factors pose a significant management challenge for SEDAPAL, in terms of both meeting the average needs of a growing population and ensuring that its system can effectively cope with drought conditions.

1.3 SEDAPAL's Long Term Water Management Strategy

Recognizing the urgency of Lima's water situation, in 2013 SEDAPAL developed an aggressive $2.3 billion Master Plan for 2015-44, which includes the implementation of 12 major infrastructural investment projects to augment supply (SEDAPAL 2013). These 12 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 a projected 25 percent increase in water demand by 2040. 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 period of 2015-20.

After the development of the Master Plan, but before its submission to national regulators, the World Bank funded a study of how the plan, plus two additional investments, would perform across a wide range of plausible future conditions, and which elements should be prioritized (Kalra et al. 2015). Based, in part, on this study, SEDAPAL is now prioritizing the implementation of some of the Master Plan's investments to increase the storage and treatment capacity of the system. The first phase of investments includes a combination of moderately-sized reservoirs and water treatment plants (WTPs), plus the enlargement of a connection tunnel. Phase 2 includes the Marca II project (table 1.1). The remaining investments are planned for after 2027.

One project identified by the World Bank 2015 study as being particularly important to meeting Lima's long-term needs was the Marca II and the Huachipa WTPs. This 90 million cubic meters project could supply up to an additional 5 m^3/s in the dry season, augmenting the Rimac supply by nearly 20 percent. Investments related to this project, however, have not yet begun as the project needs additional studies to (1) ensure the reliable availability of the water supply that would be diverted to the Rimac system (also

TABLE 1.1. SEDAPAL Master Plan's Prioritized Investments by Phase

Projects/investments	Additional system capacity in million cubic meters	Phase	Expected year of activation	Estimated cost US$, millions
Enlargement of Gratón Tunnel	30	1	2021	97
Autisha Reservoir	25	1	2020	22
Casacancha Reservoir	20	1	2020	97
Jacaybamba Reservoir	28	1	2020	145
Atarjea WTP	+2m^3/s WTP	1	2020	1.6
Marca II[a]	90, +5m^3/s WTP	2	2023	767
(Estimated) total	193			

Source: SEDAPAL 2013.
Note: The volumes and costs listed in this table will be refined further during technical feasibility studies.
WTP = water treatment plant.
[a]Includes the Pomacocha Reservoir and Obras de Cabecera. By 2023 the Pomacocha Reservoir, the Obras de Cabecera water treatment plant (5m^3/s capacity), and the trans-Andean tunnel should be built. However, the Pomacocha Reservoir will not operate at full capacity until 2027. Therefore, by 2023 it will only provide 3m^3/s extra to the SEDAPAL system, and 5m^3/s by 2027.

given actual and planned concessions in the Yauli River), and (2) identify potential impacts and develop necessary mitigations to the environment and current and future users in the origin basin.[5] The expansion of the Huachipa WTP, which could treat this additional water, is also uncertain, particularly because of the feasibility of expanding the primary and secondary network to be able to distribute the treated water. For instance, at present, although the plant has a nominal capacity of 5 m^3/s, the distribution network is only able to accommodate 1.2 m^3/s. This project, however, is SEDAPAL's largest identified source of new supply that would be needed to address growing demands over the long term. As such, this drought study considers the effect that this project would have on SEDAPAL's drought management strategy.

Currently, SEDAPAL is also implementing various projects to increase distribution efficiency and reduce losses in 150 kilometers of its distribution network. Once completed, the utility believes it will be able to reduce approximately 0.7 m^3/s of water losses. In this report, we have included the efficiency improving measures in the Phase 1 system improvements.

While these system improvements are not designed to specifically manage droughts, they are central to preserving SEDAPAL's capability for addressing drought conditions in the near and long term. Systematic reductions in water use and the development of new supplies and storage all increase the available supply during drought conditions.

1.4 SEDAPAL's Current Drought Management Strategy

SEDAPAL's existing drought management strategy relies primarily on increasing groundwater use and targeted delivery curtailments during periods of shortages. For central and eastern Lima,[6] which account for 91 percent of Lima's water supply demand and depend nearly fully on supply from the Rimac River, these actions include:

- cuts to irrigation users upstream of Lima,[7]
- activation of additional groundwater wells,
- cuts to water supply in the evening within Lima,
- water pressure reduction to reduce losses, and
- information campaigns to encourage conservation.

SEDAPAL uses a detailed set of rules to determine how, when, and for how long to implement these drought management actions. SEDAPAL's two guiding objectives are to (1) maintain a target flow of 23 m^3/s[8] in the Rimac River throughout the dry season (May-November), while (2) preserving at least 130 million cubic meters in storage by the end of the dry season (November). In the rainy season, water supply is provided by the natural Rimac River flows, occasionally augmented by groundwater pumping to ensure that upstream reservoirs fill completely. At the end of the rainy season, SEDAPAL determines how much stored water can be used in the coming dry season by calculating the difference between the total stored water and the 130 million cubic meter threshold.

Concurrently, every two weeks a SEDAPAL contractor projects the natural flows in the Rimac River for the duration of the dry season. SEDAPAL uses these projections to calculate how much water needs to be released during the dry season to ensure a supply of 23 m^3/s for the WTPs. If the available stored water—that is, the difference between the total stored water and the 130 million cubic meter threshold—is not sufficient to increase the natural flows, then SEDAPAL activates a series of drought actions. It activates these actions under the specific following conditions:

- **Regulated flows < 22 m^3/s**: Cuts irrigation upstream of Lima, reducing demand by 1 m^3/s; implements communication campaigns promoting water conservation, recovering up to 0.2 m^3/s.
- **Regulated flows < 21 m^3/s**: Activates reserve wells, augmenting supply by 1.5 m^3/s. This action is used until annual maximum additional withdrawal of 28 million cubic meters is reached. This raises the sustainable annual groundwater allotment from 70 million cubic meters to 98 million cubic meters, which is an emergency upper threshold.
- **Regulated flows < 20.5 m^3/s**: Implements nocturnal supply cuts and pressure reduction in the distribution system, recovering 0.5 m^3/s.
- **Regulated flows < 20 m^3/s**: Activates 51 extra groundwater wells, which can provide up to 8 m^3/s, but are constrained by the annual maximum additional withdrawal of 28 million cubic meters per year.

These actions are revisited every time the new projections of the Rimac River flows are produced. Different departments in SEDAPAL implement these actions under the guidance

TABLE 1.2. Summary of SEDAPAL Drought Management Actions

Drought management actions	Regulated flows in Saint Eulalia metering station (Rimac) between May and November (m³/s)					Water recovered	SEDAPAL division responsible for drought management action
	>22	22	21	20.5	20	m³/s	
Irrigation cuts						1	Reservoir Monitoring and Control Management Division (ESCP)
Information campaigns						0.2	Communication Division (ECI)
Extra groundwater						1.5	Groundwater Division (EASu), Pumping Stations O&M Division (EOMASBA)
Nocturnal cuts; pressure reduction						0.5	O&M of the Distribution Network Division (EOMR)
51 extra groundwater wells						0.8	EASu, EOMASBA

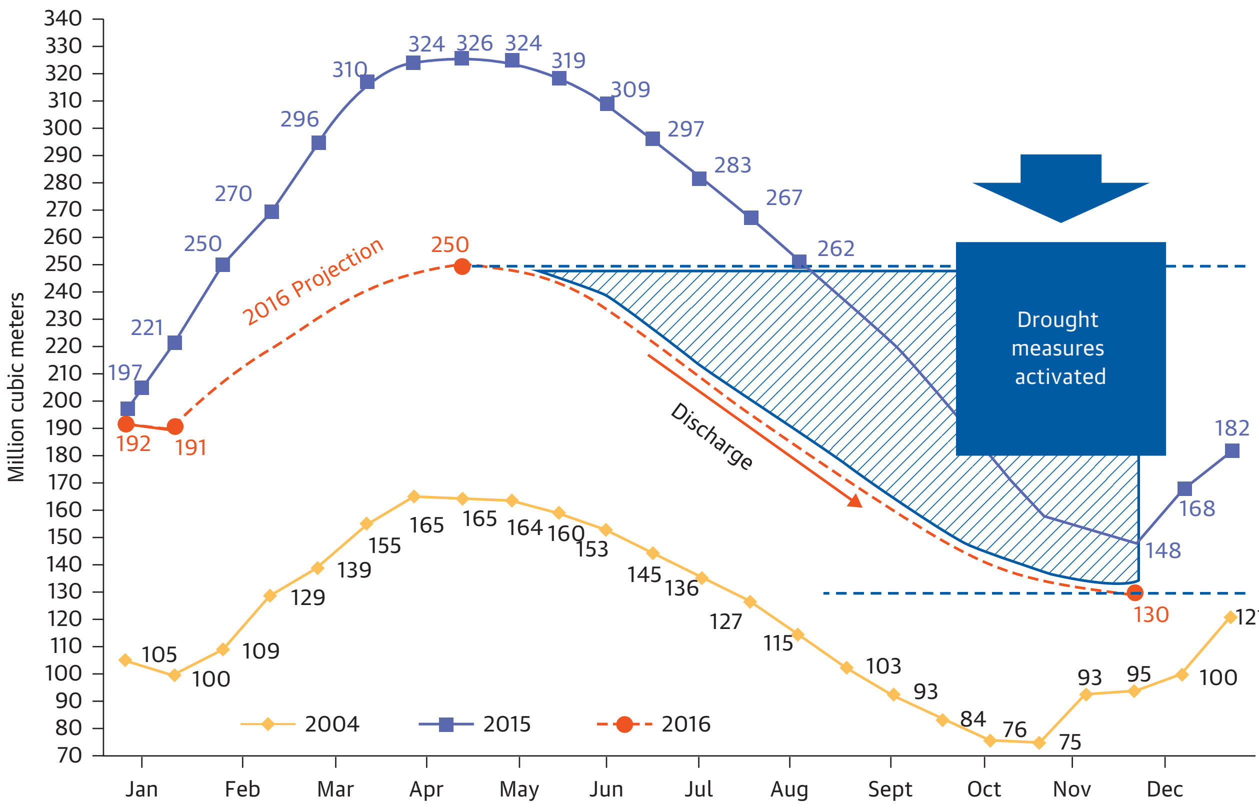
Source: World Bank and SEDAPAL workshop, October 2016.
Note: Shaded areas indicate activation of drought management action.

of the Reservoir Monitoring and Control Management Division (ESCP), the operation unit in charge of regulating the releases from the reservoirs, and the Integrated WTP Management Division (EGIP) in charge of treating the water in La Atarjea and sending it to the distribution system. Table 1.2 summarizes the drought management actions and responsible parties.

This drought management strategy relies heavily on groundwater exploitation as a buffer for scarce surface water supply. Historically, groundwater had been used in the central areas of Lima year-round at average rates that often exceeded 6 m³/s. During the rainy season, groundwater was used to allow reservoirs to fill more quickly, while during the dry season, it was used to complement the insufficient surface water released from reservoirs.[9] However, during the 1990s and early 2000s, groundwater levels in Central Lima were dropping fast, indicating that such intensive use was not sustainable. In response to dropping groundwater levels, SEDAPAL instituted an average pumping rate limit of 2.2 m³/s (70 million cubic meters per year under normal conditions) in 2004, though pumping generally continued at a steady rate year round. The new operations include provisions for drought response and during drought conditions SEDAPAL can withdraw up to an additional 28 million cubic meters per year. This increase in groundwater withdrawals can only be performed for two consecutive seasons in order to avoid depletion of the aquifers. Moreover, after 2013, when new storage was brought online (see box 1) changes were made to prioritize surface water use during the rainy season given the large amount of runoff and utilize groundwater only during the dry season to supplement the use of stored surface water.

This strategy has enabled SEDAPAL to successfully manage recent drought conditions. For example, it helped SEDAPAL manage drought conditions accompanying the 2015-16 El Niño event. As evidence of the effectiveness of these actions, even though the 2015 wet season

FIGURE 1.1. Illustration of Rimac Reservoir Storage for 2004, 2015, and 2016 and the Activation of Drought Measures in 2016



Source: SEDAPAL 2016.

brought little rain and stored volumes were only 60 percent of total capacity at the end of April (figure 1.1, orange line), SEDAPAL was able to manage its system to meet the 130 million cubic meters storage target by November 2016. Figure 1.1 further shows that in April 2016, SEDAPAL could use only 120 million cubic meters of stored water, which alone were not sufficient to secure the city's supply. Therefore, in May it activated the drought actions mentioned above and reduced the releases from the reservoirs. This allowed the utility to preserve the target at the end of the 2016 dry season without affecting water users.

1.5 A Forward-Looking Evaluation of SEDAPAL's Drought Management Strategy

Although these actions have been effective in buffering recent moderate and short droughts, SEDAPAL is aware of its need to augment its drought management plan to help optimize available resources and prioritize management actions. In December 2016 (during this analysis), for example, rains failed to arrive when expected, putting the system under enormous stress. In response, 8 m^3/s emergency groundwater pumping was introduced, in addition to the other called-for drought actions, pushing the system to its limit until the rains came.

This emergency situation highlighted even more the case for a well-structured, proactive drought management plan that would, in addition to other benefits, help protect groundwater sources.

Therefore, SEDAPAL worked with the World Bank to evaluate how its current drought management plan could be augmented to meet future challenges. This study builds upon SEDAPAL's current drought management plan by exploring how it could be modified and augmented to perform well under future conditions in which water demands are higher and drought conditions possibly different from those in the past.

This study takes a forward-looking approach to evaluate how SEDAPAL's current drought management strategy would perform over a wide range of plausible futures in order to understand how best to augment the strategy to ensure successful future drought management. To do so, we use the Decision Making under Deep Uncertainty (DMDU) method, specifically Robust Decision Making (RDM), to first evaluate how SEDAPAL's current drought management plan would perform across a range of uncertain futures (Groves and Lempert 2007; Lempert et al. 2006). Next, we identify the key vulnerabilities in terms of those future conditions that lead to unacceptable performance during drought periods. Lastly, we compare how new management actions could improve its performance and weigh different trade-offs. This contrasts with the standard approach of evaluating how the most recent drought of record would affect a water system and then optimizing operations to ensure an acceptable outcome.

This study's design was also informed by lessons learned from a recent World Bank project on drought management in Northeast Brazil (De Nys and Engle 2015). The Brazilian study focused on helping stakeholders in Brazil (both at the national level and more specifically in the Northeast region) develop and institutionalize proactive approaches to drought events, with the ancillary benefit of developing tools, frameworks, processes, and exchange platforms from which other countries and World Bank sectors/regions could learn and eventually foster innovation around this topic. The drought preparedness plans (also called contingency plans) developed with the support of this study define the types of actions to be taken for the different stages or intensities of drought (that is from the first signs of drought to extreme and exceptional droughts to periods of non-drought), as well as the initiation and termination conditions for each stage.

The five case studies and associated drought preparedness plans presented in this report were developed and operationalized through dialogue with different sectors and at different levels of decision making. The five case studies include two urban water utility case studies of the Fortaleza Metropolitan Region and the Agreste Region of Ceará and Pernambuco; two cases associated with the Piranhas-Açu River Basin that is shared with Paraíba and Rio Grande do Norte—a basin-wide drought preparedness plan and a plan for a small water storage reservoir (*açude*) for multiple uses (i.e. potable water versus irrigation), named the Cruzeta; and a plan for rainfed agriculture for the city of Piquet Carneiro in central Ceará.

All of the drought preparedness plans produced with the support of the World Bank in Brazil include drought impacts and vulnerabilities, key institutional actors, planning measures for mitigating drought risk, and emergency responses. The ultimate intention is that they will be used to guide decisions as the next drought unfolds, and also to help guide long term investments that address underlying vulnerabilities and mitigate future drought risks. The plans are also expected to help drive the conversation amongst federal and state governments on how to scale up these examples across the region and country. While the two urban water utility case studies in the Fortaleza Metropolitan Region and the Agreste Region of Ceará have provided particularly useful insights for preparing for future droughts in Lima—specifically in terms of methodological approaches to drought contingency planning studies and characterizing drought at this level of decision making—the Brazilian case studies share the common conclusion that the next logical step would be to better incorporate methods for addressing uncertainty in a quantitative way. In this sense, the approach and analysis presented here with respect to Lima builds from and improves upon what the Bank has supported to date in Brazil.

Given that SEDAPAL is the direct client of this work, this analysis focused on (1) assessing the vulnerability of their system to drought and (2) planning for water delivery-related risk preparedness and management. As a result, the study begins by evaluating the pitfalls and strengths currently faced by SEDAPAL in its management of water delivery under drought conditions; next it identifies SEDAPAL's available options. However, it is unlikely that SEDAPAL alone will be able to offset the impacts of a severe drought, and the plan should be implemented in cooperation and coordination with other institutions, like the National Water Agency, NGOs working in the watershed, or the hydropower company ENEL. Importantly, the monitoring and forecasting of a drought, or the development of an early warning system, needs to be developed jointly with the National Weather Service and Hydrology of Peru (SENAMHI). This study, which provides the analytical basis that SEDAPAL can use to drive conversation with the other agencies, therefore recommends these partnerships to develop an integrated drought preparedness and management plan.

Following best practices in decision support, this project embedded analytics within an intensive and structured participatory process in cooperation with SEDAPAL and other stakeholders (National Research Council 2009). The study began in May 2016 and the analysis was completed in August 2017. This project kicked off with a multi-day workshop at SEDAPAL in September 2016 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 chapter 2.2. We launched the data gathering efforts needed to use the Water Evaluation and Planning (WEAP) software tool. 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 May 2017, we held another set of workshops in which we presented preliminary findings from the vulnerability analysis with and without the revision of SEDAPAL's current drought management action, to include the set of measures identified in October 2016 and during several exchanges in the following months. We presented the work to SEDAPAL's management and other stakeholders interested in the study, including Peru's National Water Authority (ANA), the water supply and sanitation regulatory authority (SUNASS), representatives of river basin organizations, and local nongovernmental organizations and municipal authorities. We adjusted the scope of the analysis based on their feedback. Moreover, between September 2016 and May 2017, we had weekly or bi-weekly exchanges with the SEDAPAL team. This frequent interaction enabled us to ensure that the analysis answered questions that were most important to SEDAPAL and most practical for their planning. Importantly, it enabled us to confirm that the model adequately simulated the system and its operations. It also enabled SEDAPAL to use interim results as part of their ongoing internal planning activities.

Notes

1. See https://www.cia.gov/library/publications/the-world-factbook/geos/pe.html.
2. Based on available flow data from 1966-2009.
3. "Managed lakes" are those connected to the SEDAPAL system via canals and diversion structures.
4. These are the official numbers, but there are also many more illegal, non-registered ones.
5. However, the IFC began structuring a financing package in 2017.
6. The other two areas of Lima are mostly supplied by groundwater during the dry season, hence they are currently less dependent on stored water. Hence, this study focuses mostly on central and eastern Lima, supplied primarily by the Rimac system.
7. According to SEDAPAL, what is labeled as "irrigation use" mostly consists of gardens, parks, and hobby agriculture, reducing the effects of cutting back for end users.
8. Currently, the average production of La Atarjea and Huachipa WTPs is approximately 18.7 m^3/s (SEDAPAL 2016). La Atarjea treats on average 17.5 m^3/s and Huachipa 1.2 m^3/s. SEDAPAL wants to maintain at least 22 m^3/s in the Rimac because, between the measuring station at Chosica and the WTPs, other users divert 3 to 4 m^3/s.
9. Note that storage capacity then was lower than it is today (see box 1.1).

Chapter 2 Methodology and Scope of the Analysis

2.1 Drought Planning

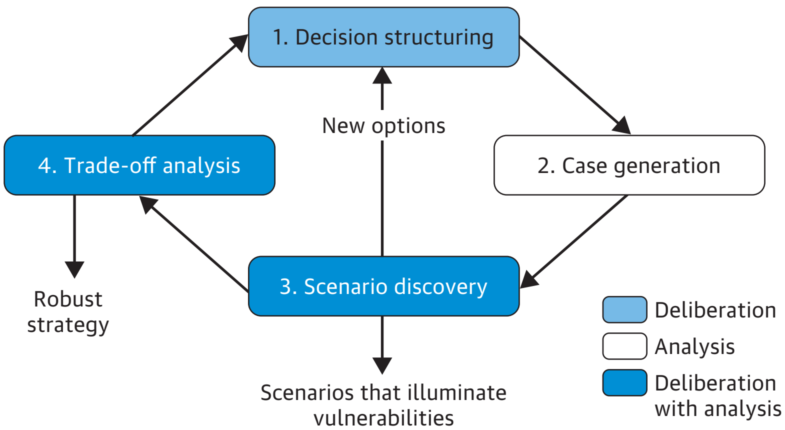
The slow onset of droughts has led to drought management approaches that are relatively reactive compared to other climate-related disasters (Wilhite et al. 2014). As a result, the relevant institutions are traditionally mobilized to develop and implement emergency actions to mitigate economic and social losses only after a given region is already engulfed in drought. This is often referred to in the drought literature as the "hydro-illogical" cycle. On the other hand, the idea of drought preparedness has gained increasing attention as it takes a proactive risk management approach to drought policy and planning through its emphasis on: (1) monitoring and forecasting/early warning; (2) vulnerability/resilience and impact assessment; and (3) mitigation and response planning and measures. Systematically building drought preparedness policies and approaches across different levels of decision making can ultimately increase the resilience and adaptive capacity of water systems, and help reduce economic losses and costs associated with more reactive disaster response and recovery (Engle 2013). For example, as illustrated by a recent analysis on hydro-meteorological monitoring systems, the development and deployment of modern monitoring systems across all developing countries could generate a benefit-cost ratio of between 4:1 and 34:1, or between $4 billion to $36 billion in benefits per year (Hallegatte 2012).

Despite this increased emphasis on drought preparedness, drought plans are often developed and evaluated based on the drought of record (the most significant historical recorded drought) and do not specifically consider how more severe or frequent droughts, or other uncertainties, would impact drought preparedness. For example, the Brazil drought preparedness plans described above do not consider changes in the underlying hydrology or other inevitable and uncertain changes, such as supply, demand, climate, and infrastructure. SEDAPAL's current drought management strategy has also been developed based on historically-recorded conditions and have not, prior to this study, been evaluated under alternative conditions.

2.2 Decision Making under Deep Uncertainty (DMDU)

This study uses Robust Decision Making (RDM)—a methodology for DMDU—to structure an analysis of over 14,000 different conditions reflecting plausible future drought sequences, trajectories of water demand, and level of infrastructure development. RDM is an iterative, analytic approach for developing plans that will perform well across a wide range of plausible future conditions (Groves and Lempert 2007). RDM has been used to develop long-term water management strategies in a variety of contexts, including Lima (Kalra et al. 2015); the Colorado River Basin (Groves et al. 2013); and African river basins (Cervigni et al. 2015). Other related approaches have been applied in the United States and elsewhere, for instance in the Great Lakes region (Brown et al. 2011), The Netherlands (Haasnoot 2013), the Niger River Basin (Brown 2011), and Brazil, Kenya, and Nepal (Hurford 2016).

FIGURE 2.1. How to Apply the Robust Decision Making Methodology



Source: Lempert et al. 2013.

Figure 2.1 shows the key steps of applying the Robust Decision Making methodology: (1) structuring the decision; (2) evaluating outcomes over many futures; (3) identifying key vulnerabilities, which informs the development of new options; and (4) weighing the trade-offs among the most robust choices. The study used this approach to thoroughly stress test SEDAPAL's current drought plan against a range of plausible future conditions, and then to evaluate the merits and trade-offs of several different types of drought management improvements, including operational changes, new infrastructure, and conservation.

RDM studies often summarize the scope of the analysis (from Step 1) using a theoretical framework called XLRM, whose components include uncertainties (Xs); actions or levers (Ls); system models (Rs); and performance metrics (Ms). For this analysis, the key uncertainties include changes in hydrology and the implementation of system improvements. The performance of the SEDAPAL system, including its drought management, is evaluated using a model developed by the Water Evaluation And Planning (WEAP) modeling system.[1] The key performance metrics are unmet water supply demand across four periods of time: the recent historical period (2002-16) (for calibration and reference purposes),[2] the near term (2017-21), the intermediate term (2022-26), and the long term (2027-40). We evaluate the current drought management plan under the currently configured system, one with near-term system improvements from the Master Plan (Implementation Phase 1 of table 1.1), and one with long-term system improvements from the Master Plan (Implementation Phase 2 of table 1.1). We then evaluate different sets of drought management actions. Table 2.1 summarizes the scope of analysis.

Several different research activities were undertaken to support the analysis and generate the study's results. First, we developed new sequences of water inflows to represent different plausible drought conditions (see chapter 2.3). Concurrently, we updated an existing water management model developed for a prior study that evaluated SEDAPAL's long-term Implementation Plan (Kalra et al. 2015) (see chapter 2.4). We refined this model to evaluate

TABLE 2.1. Scope of This Study's Robust Decision Making Analysis, Based on the XLRM Framework

Uncertainties (X)	Actions or levers (L)
Sequences of water inflows • Historical sequence • Synthetic sequences reflecting changes in drought frequency and intensity System improvements • Near-term efficiency improvements and infrastructure • Long-term infrastructure (large storage)	Drought management actions and investments • Additional emergency conservation • Alternative operations of reservoirs • New drought storage reservoirs
System model (R)	**Performance metrics (M)**
Water Evaluation and Planning (WEAP) model applied to the SEDAPAL system	Unmet water supply demand • Recent historical (2002–16) • Near term (2017–21) • Intermediate term (2022–26) • Long term (2027–40)

the performance of droughts with respect to dry years (see section 2.5). We then worked with SEDAPAL to develop and model new drought management options (see section 2.6). Lastly, we specified and performed a set of experiments that would test different drought management plans across a range of futures (see section 2.7). Along the way, we developed an interactive decision support tool to explore results and identify robust augmentations (see section 2.8).

2.3 Uncertainties (X)

The analysis considered two main uncertainties—future hydrological conditions and the implementation of system improvements identified in SEDAPAL's Master Plan (2015-44).

2.3.1 Alternative Future Hydrological Conditions

We developed a large set of different future drought sequences to represent plausible future hydrologic conditions. These future drought sequences include both historically-cycled records—with specific historical droughts placed in specified years—and synthetically-generated random hydrological sequences that modify the historical statistical properties of observed historical sequences. These sequences include records for all hydrologically variable inflows to the model.[3]

Available streamflow records for the Rimac system from 1966 to 2009 were obtained from SEDAPAL. Streamflow records from 2010 to 2016 were synthetically generated to complete the historical record (1965-2016). We used SEDAPAL guidance on the similarities between precipitation and streamflow in years historically available and observed but not formally recorded conditions during 2010-16 to modify the synthetically generated records to better reflect and simulate this historical period.

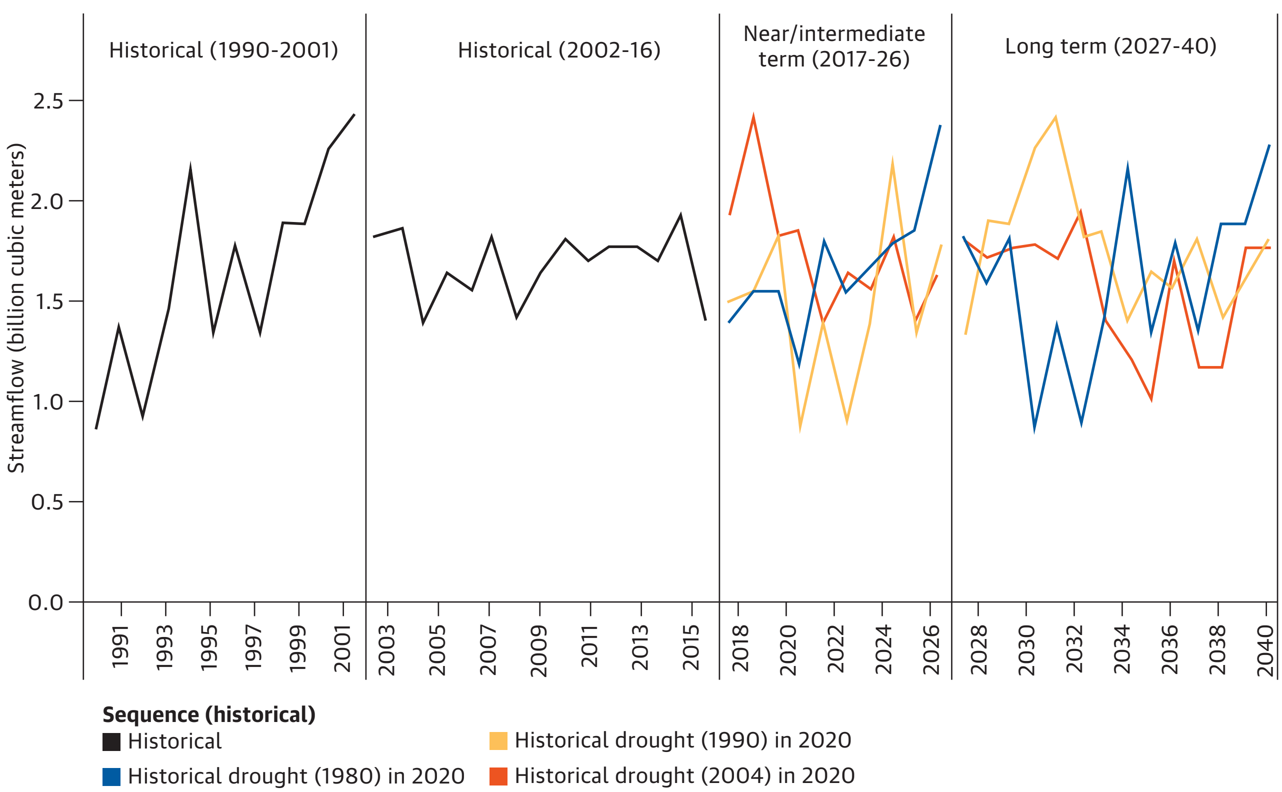
2.3.1.1 Historical Hydrological Inflow Sequences

Selected portions of historical streamflow records were used to generate three plausible future drought sequences. These sequences were generated by repeating historical inflows so that significant droughts from historical years—1980, 1990, and 2004—are specified to occur in 2020. For example, the hydrologic sequence placing the 1980 drought in 2020 was generated by appending hydrologic records from 1977-2000 to the existing record (1965-2016). Figure 2.2 shows the total system inflow across the three historically consistent sequences included in the model. Note that the sequences only differ in the future time periods.

2.3.1.2 Synthetic Hydrological Inflow Sequences

Synthetic future inflow sequences were generated to evaluate how potential changes to the intensity and frequency of wet and dry periods could impact the SEDAPAL water management system. We used a slightly modified method of Herman et al. (2016) to create the synthetic hydrological sequences, as this method provides a simple way to adjust the frequency in which dry and wet months appear in an otherwise random, but historically consistent sequence.[4] We used this method to develop sequences with different frequencies of dry and wet months. We then used the Delta Method (Anandhi et al. 2011) to modify these sequences to reflect more intense dry and wet periods.

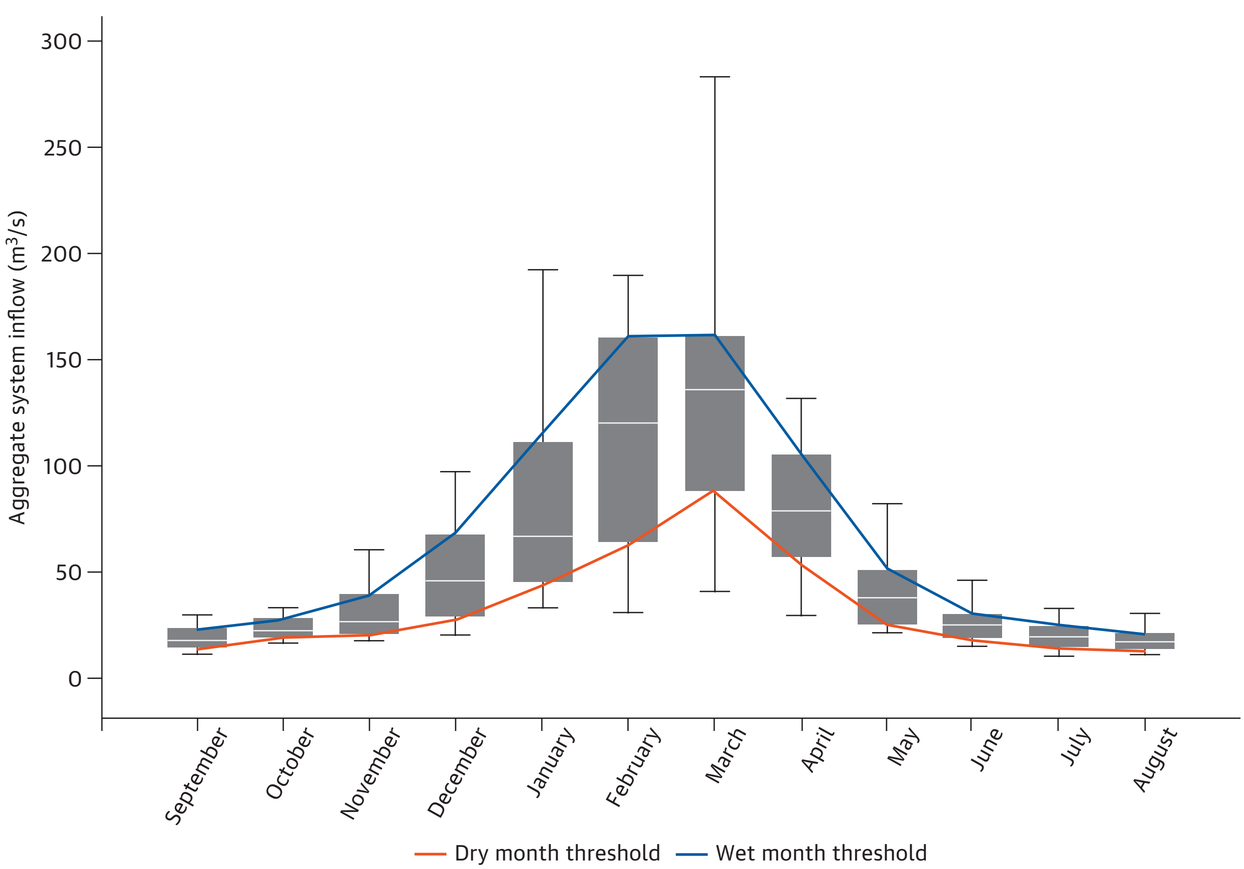
FIGURE 2.2. Inflow Sequences Based on Historical Records



To implement this method, we first classified the historical hydrologic record in terms of dry, wet, and normal months. Dry months were defined as those where aggregate inflows were in the bottom 15 percent of flows across all years; wet months are those in the top 15 percent, and normal months are the rest. The thresholds used to define each month as dry or wet vary by month and are shown in figure 2.3 along with distributions of monthly aggregate inflow across all years available in the hydrologic record.

This classification of months was then used with the Herman et al. (2016) methodology to develop 10 random sequences by sampling historical values for each month, generating a sequence, and adjusting to preserve the autocorrelation of the historically observed records. As part of the methodology, dry and wet months can be sampled more frequently in order to generate random sequences of drier, wetter, or more extreme streamflow records. Changes to the frequency of dry/wet months are obtained by changing the sampling weight of dry/wet months. The dry months sampled more heavily to generate synthetic records with a dry year frequency increase lie below the orange line in figure 2.3, while wet months sampled more frequently to generate wetter synthetic sequences lie above the blue line.

FIGURE 2.3. Distributions of Aggregate System Inflow, 1966–2009, with Dry (15th Percentile) and Wet (85th Percentile) Thresholds

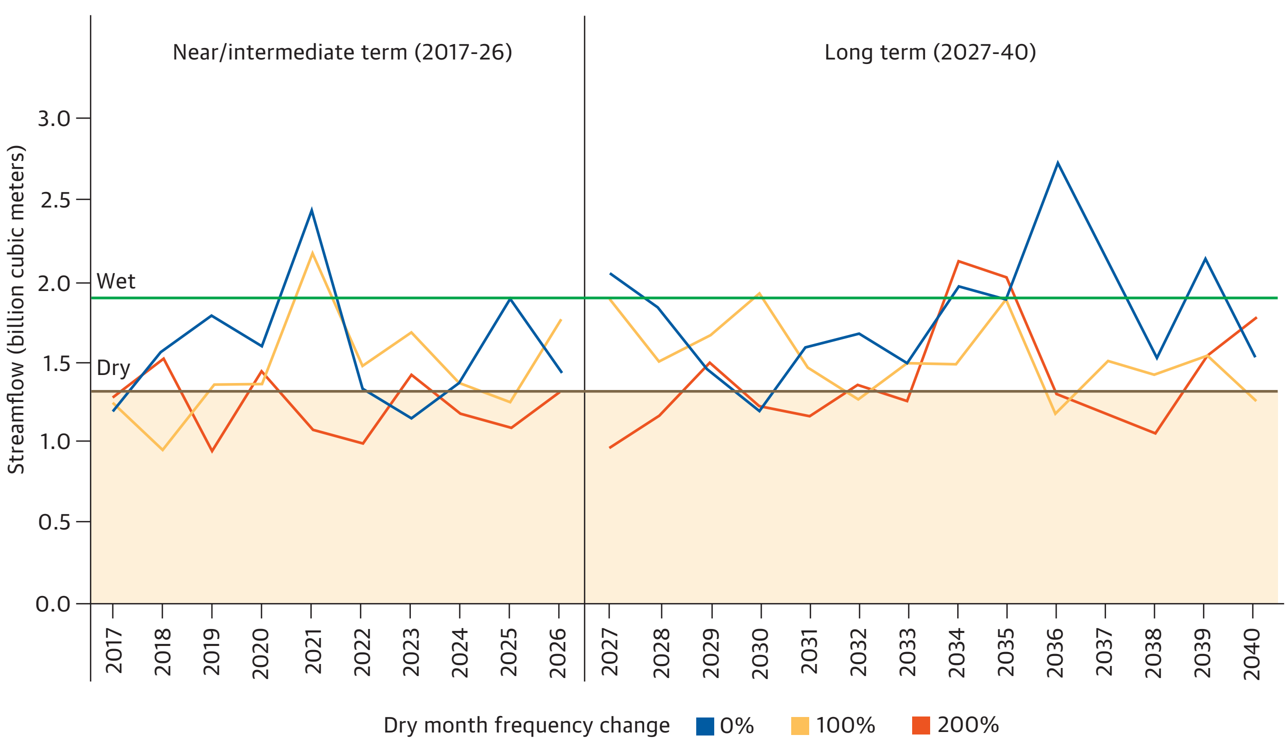


We developed the following six combinations of dry and wet year frequency changes:

- No change in frequency
- 100 percent increase in frequency of dry years
- 200 percent increase in frequency of dry years
- 100 percent increase in frequency of dry and wet years
- 200 percent and 100 percent increase in frequency of dry and wet years, respectively
- 200 percent increase in frequency of dry and wet years

For each combination of wet and dry sampling weights, random sequences were generated to ensure variability across the records. Figure 2.4 shows three synthetic sequences with 0, 100 percent, and 200 percent increase in the frequency of dry months. Note that while this method does not explicitly vary the duration of drought periods, increasing the frequency of dry months does lead to longer droughts. The average streamflow for these three sequences (between 2017 and 2040) is: 1.70 m^3/s, 1.5 m^3/s, and 1.33 m^3/s, respectively, reflecting the increased frequency of dry months in the second and third sequences. Note that the two sequences with increased frequency of dry periods lack a significant wet year. This is a function of the randomness of the sampling, as all three sequences still reflect an equivalent sampling of wet periods.

FIGURE 2.4. Three Synthetic Sequences with Different Frequencies of Dry Months



Secondly, to implement changes to drought intensity, years were classified as wet, dry, or normal in each hydrological record used for modeling. Dry and wet years were defined using thresholds calculated using total historical annual inflows for hydrologic years (September to August). The dry and wet thresholds were calculated from historical records and defined as the bottom and top 15th percentiles, approximately 1.33 billion cubic meters per year and 1.89 billion cubic meters per year, respectively (shown as red and green lines in figure 2.4).[5] Changes to intensity were then applied only to wet and dry years using specified deltas and were additionally adjusted to increase in magnitude over time, reaching the specified delta by 2035. We considered 11 different specifications for intensity changes, coupled with the 6 frequency changes:

- No intensity change
- 10 percent, 20 percent, 30 percent, 40 percent, and 50 percent decline in precipitation during dry periods
- 10 percent, 20 percent, 30 percent, 40 percent, and 50 percent decline in precipitation during dry periods paired with 10 percent, 20 percent, 30 percent, 40 percent, and 50 percent increase in precipitation during wet periods

To focus the analysis on conditions that would stress the current drought management plan, we only considered increases in intensity and frequency of wet periods when accompanied by increases in intensity and frequency of dry periods.

2.3.2 System Improvements

We developed two phases of system improvements. The first phase represents investments that are already underway and could be mostly completed by 2020, including efficiency improvements and other Master Plan investments that benefit Central and Eastern Lima's supply: the Autisha and Casacancha Reservoirs, the enlargement of the Atarjea WTP, and the enlargement of the Graton Tunnel.

The second phase includes additional large-scale supply and storage identified in the Master Plan: Marca II and the expansion of Huachipa WTP. Due to their complexity, scale, and potential adverse social and environmental impacts, these projects would not likely be implemented until 2023, if they are deemed at all feasible (see section 1.3 for more details on these investments).

In this analysis, we did not consider the 10 remaining Master Plan investments, which would come into operation after 2027.

2.4 System Model (R)

We use a water management system modeling tool to evaluate the performance of SEDAPAL's current and revised drought management plan. An interactive, analytic decision support tool (described below) provides visualizations of key results, including the trade-offs between cost-effectiveness and implementation and cost constraints.

A WEAP water management model of the SEDAPAL system was developed to evaluate the SEDAPAL Master Plan through 2040 (Kalra et al. 2015). The original 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 major water infrastructure, including five reservoirs in the Alto Mantaro, two groundwater basins, and all canals and transfer tunnels of the Marca I, II, III-V,[6] including a trans-Andean tunnel. The model also contains the existing water treatment plants of Atarjea, Huachipa, and Chillón. Additionally, each of the 12 proposed Master Plan projects (plus Cañete transfer/WTP and the Chancay Reservoir) can be modeled individually or in different combinations.

For this project, we collaborated with managers and technical staff at SEDAPAL to improve the model to better reflect detailed systems operations and drought management. Modifications to the model included:

1. Changes to the schematic to represent additional planned infrastructure. These include additional reservoirs in the Marca III project area to represent five reservoirs that SEDAPAL is considering constructing to provide drought resilience: Puagjanca, Cauquis Machay, Tuctococha, Chuquicocha, and Gallo Huaganan.[7]
2. Changes to improve the modeling of system operations. The original WEAP model of SEDAPAL (Kalra et al. 2015) was constructed to evaluate the performance of large scale infrastructure projects over the long term. In order to evaluate the ability of the system to meet demands under short term drought conditions, the model was refined to reflect short term operational rules for drought management. Operational rules were added to the model to reflect measures and actions currently undertaken by SEDAPAL in response to drought conditions. Additionally, these operational rules, which include management actions triggered based on environmental conditions, were calibrated using selected historical actions.
3. The addition of internal logic that implements general operational rules for the system, including drought response measures.
4. The addition and modification of metrics that highlight drought performance and resilience. We added drought management action triggers, environmental conditions used to trigger actions, supply deliveries, and different storage (for example groundwater and reservoir) metrics.

The updated model includes 7 demand nodes, 34 rivers, 26 reservoirs and lakes, 33 diversions (including tunnels and canals), and 5 groundwater basins. Although we have increased the granularity on the demand/distribution side, the model does not completely represent all details of the distribution system. Moreover, the model still operates on a monthly time step, which limits its ability to evaluate some possible strategies such as increasing the capacity of small urban reservoirs.

We also developed computer code to evaluate the WEAP model using Amazon.com's cloud-based analytical services, allowing the simultaneous running of up to a 100 cases simultaneously. As described below, our experimental design consisted of about 14,000 different specifications of policies, future demand, and hydrologic conditions. We used the WEAP outputs to create a database of the system's performance (for example unmet demand under different thresholds) for each drought action and strategy under the future plausible drought sequences.

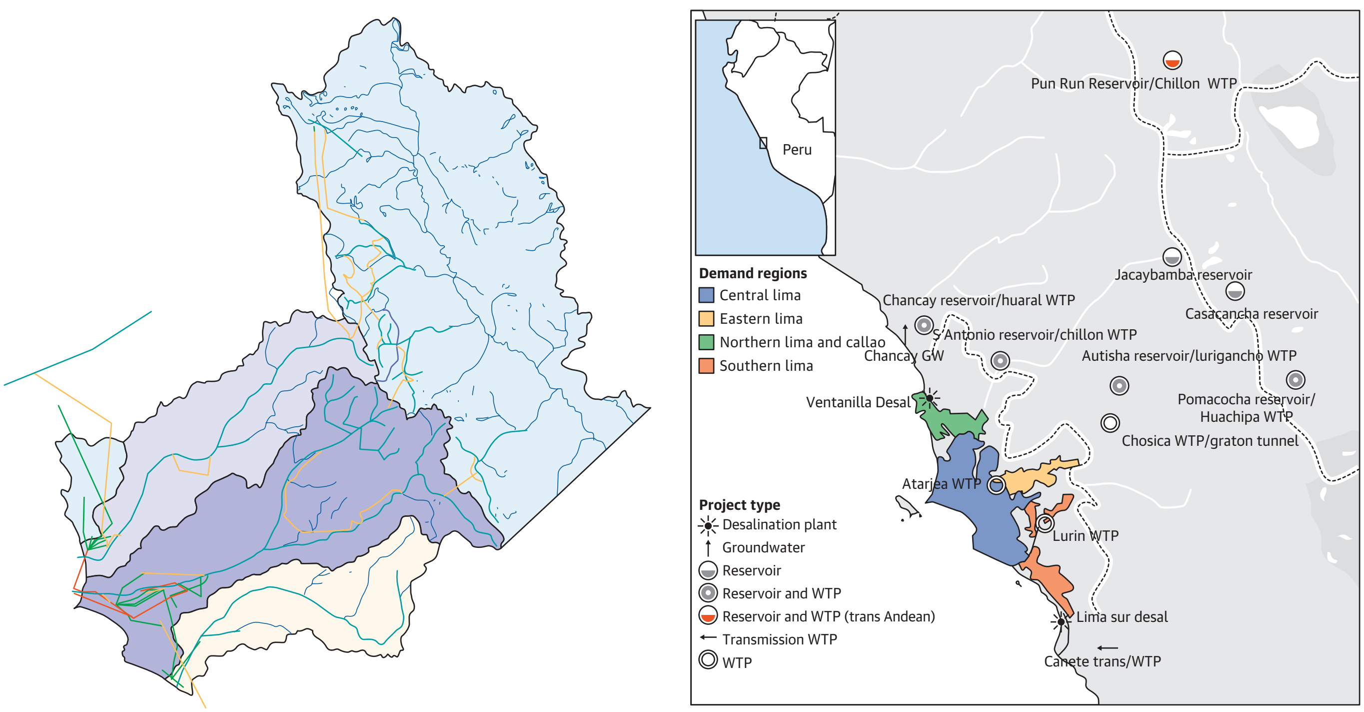
Map 2.1 shows the revised WEAP model schematic on the left and a schematic from Kalra et al. (2015) showing the demand regions and locations of the different SEDAPAL Master Plan investments (SEDAPAL 2013). The upper watersheds that bring water to the Rimac River (Marca I-V) are shaded purple; the Lurin watershed, which brings water to Southern Lima is shaded yellow; and the Chillon watershed, which supplies Northern Lima, is shaded green.

The model uses a single linear projection of water demand from current levels—estimated in the Master Plan to be 855 million cubic meters per year—to the Master Plan's projected demand in 2044—1,125 million cubic meters per year. This projection, based on population and income estimates, may be considered high and thus conservative for drought planning. In 2016, the average treated water distributed by SEDAPAL was 22.84 m^3/s, 18.5 m^3/s of which came from surface

MAP 2.1. WEAP Model Schematic of SEDAPAL's Watersheds and Aggregated Water Distribution Areas and SEDAPAL Master Plan Investments

a. SEDAPAL watersheds

b. Water distribution and Master Plan investments



Note: WTP = water treatment plant.

water and the rest from groundwater (SEDAPAL 2017). This is approximately 15 percent lower than the estimates used in the Master Plan.

2.5 Performance Metrics (M)

To represent the performance of different SEDAPAL drought management plans, we used the WEAP model to calculate how much total unmet demand would occur during the dry years in the near term (2017-21), intermediate term (2022-26), and long term (2027-40). To better capture the drought-related unmet demand, we further disaggregated total unmet demand into its two components:

- **Hydrologic unmet demand:** Captures unmet demand induced by a shortage of (regulated) surface water availability in the Rimac River. The hydrologic unmet demand is therefore the difference between the target 23 m^3/s that SEDAPAL monitors to activate drought measures and the amount of water in the river at Chosica.
- **Systemic unmet demand:** Captures the difference between the total unmet demand and the hydrologic unmet demand. In general, systemic unmet demand represents the component of unmet demand that can be attributed to systemic and operational constraints. This happens for instance where the distribution system is not fully developed, such as in the areas potentially served by the Huachipa WTP, or when the treatment capacity is lower than the available supply needed to meet demand.

Unless explicitly clarified, in the rest of the report "unmet demand" refers to hydrologic unmet demand. As there is no specific stated level of acceptability when evaluating SEDAPAL's drought management plans in the future, we defined a range of dry-year average unmet demand thresholds (from 1 m^3/s to 5 m^3/s) to characterize the performance and vulnerability for each individual simulation.

2.6 Drought Management Actions and Investments (L)

There are different actions that SEDAPAL could implement to prepare for and manage drought. These include demand and supply measures, such as reducing leaks and increasing storage, but can also include protocols for operating the system differently in anticipation of or during a drought. SEDAPAL is already investing in both reducing losses at the system level and increasing storage. Together with SEDAPAL, we identified three main actions that they could consider adding to their drought management portfolio: emergency conservation, alternative operations of reservoirs, and new drought storage.

2.6.1 Drought Conservation

SEDAPAL estimates that an aggressive drought conservation strategy could reduce demand during the dry season by 10 percent if irrigation services are cut at any time during the dry season. Once introduced, this measure remains active until the end of the dry season. For example, if irrigation services are cut in July, the drought conservation is triggered and continues through December of the same year. In practice, these regulations would also target outdoor water uses. As a reference, in 2015, California mandated an emergency 25 percent cut in cities' water use, 50-80 percent of which traditionally is outdoor water use. This measure requires upstream institutional coordination to implement, and resources set aside to enforce it (for instance, via extra surveillance around the city). These additional emergency demand management would cost about $3 million.

2.6.2 Alternative Reservoir Operations

SEDAPAL could refine the management of its reservoirs to provide more flexibility in storing water in wet periods to be able to supply more water during drought periods. This would require negotiation and coordination with ENEL. Currently, SEDAPAL and ENEL manage releases based on a compromise between SEDAPAL's need to save water for eventual emergencies and ENEL's electricity production objective. In some cases, releases are fixed. For instance, Huascacocha, which is privately owned, always releases at least 2.48 m^3/s. In others, they may vary within a contractual range and are renegotiated during the dry season to accommodate actual flows and updated projections for the months ahead. During wet years, this can allow excess water to runoff to the ocean, and, at times, it may even leave more water in the reservoirs than needed.

The goal of this option is to produce a pragmatic system for balancing resilience with optimal system operation, avoiding both unnecessary rationing and supply collapse. The option is focused on storing water during wet years, ensuring that reservoirs are filling. This is achieved primarily by modifying SEDAPAL's managed flows to minimize the amount by which they exceed their flow target (23 m^3/s in 2017).

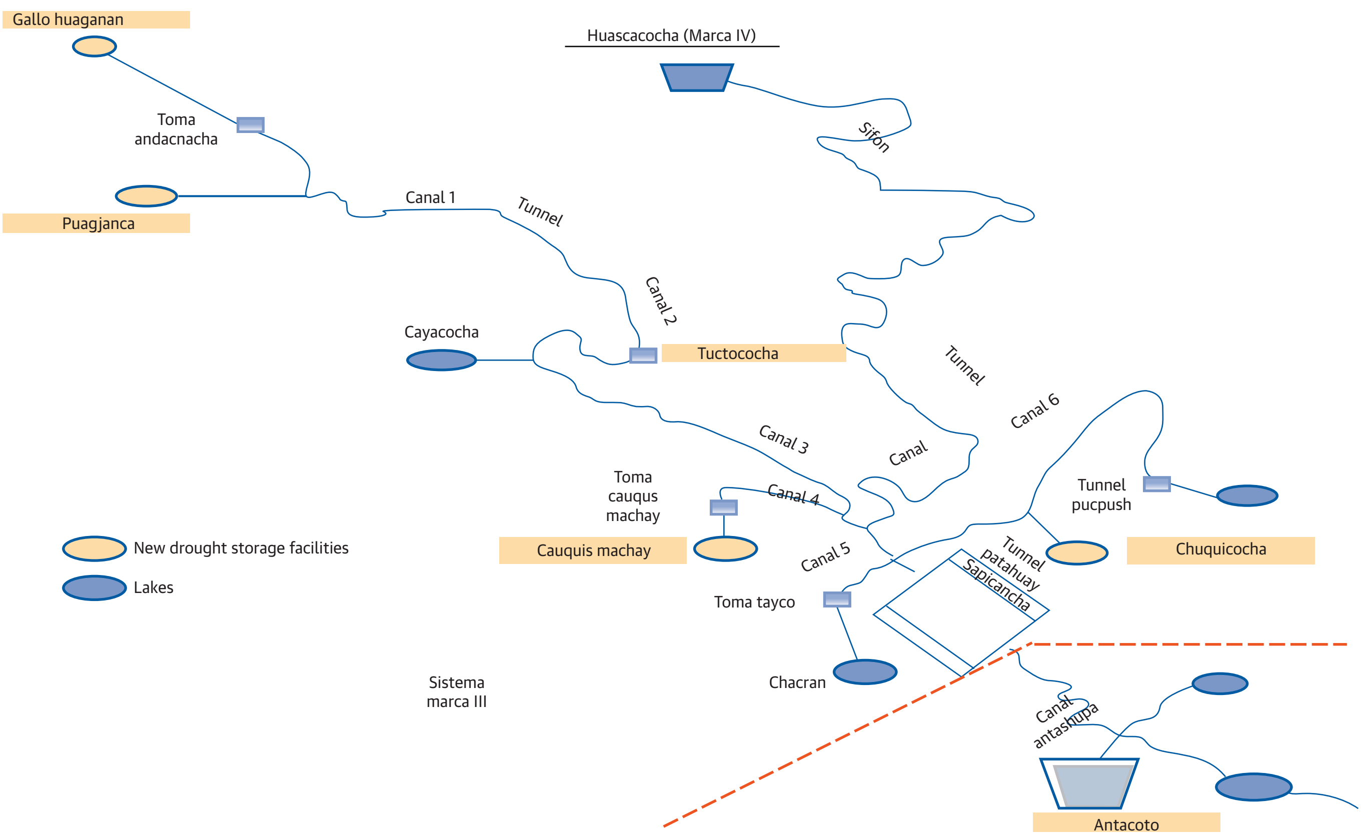
SEDAPAL could also adjust its drought triggers to account for additional system storage. Increasing storage via Phases 1 and 2 of system improvements (via the Autisha, Casacancha, and Pomacoca Reservoirs), should increase the potentially available regulated flows in the Rimac River and therefore increase available supply for Lima's municipal use. If the November threshold remained at 130 million cubic meters, significant water would be released to the ocean, despite the additional storage. Therefore, we raised the threshold gradually, proportional to the additional storage capacity that comes online: 143 million cubic meters when Phase 1 comes on line and up to 173 million cubic meters, once Pomacocha is activated fully.[8]

This option includes the installation of measuring equipment in key locations to help measure inflows and releases more accurately. SEDAPAL estimates that this option could be implemented at a current cost of $5 million.

2.6.3 New Infrastructure

SEDAPAL may also develop new storage infrastructure aimed at improving drought resilience, as opposed to infrastructure that is part of SEDAPAL's Master Plan and addresses general supply concerns. SEDAPAL is currently considering adding 30 million cubic meters of additional reservoir storage and expanding the Antacoto Reservoir to store an extra 15 million cubic meters.

FIGURE 2.5. **Schematic of Potential New Drought Storage Facilities**



Source: SEDAPAL 2017a.

New storage is created by connecting the water naturally stored by five additional lakes (Puagjanca, Cauquis Machay, Tuctococha, Chuquicocha, and Gallo Huaganan) to the rest of SEDAPAL's system. These lakes would bring additional water to the Antacoto Reservoir. As drought infrastructure, SEDAPAL will be able to utilize their naturally stored water under drought conditions. The WEAP model assumes that this water becomes available if irrigation services are cut (first dry season drought trigger). Figure 2.5 shows a schematic of these five lakes.

The Yantac Tunnel, which would transfer water stored in a mountain aquifer (the Jumasha Formation) to Rio Chillón (SUNASS 2015), with a 6 m^3/s transfer capacity, is also included. These infrastructure investments would cost $129 millon.

2.6.4 Drought Management Strategies

Based on these individual options, we developed five drought management strategies, comprised of different combinations of the individual options listed above and assuming as a baseline the current drought management actions. As shown in table 2.2, the first four strategies incrementally add options to the baseline, starting with those that are generally less difficult to implement. The final strategy calls for implementing only the costliest

TABLE 2.2. Drought Management Strategies

	Current drought management	Emergency 10% reduction in demand	Alternative reservoir operations	New drought reservoirs
A) Current drought management (CDM)	✓			
B) Add drought conservation (CDM + DC)	✓	✓		
C) Add reservoir reoperations (CDM + DC + Reop)	✓	✓	✓	
D) Add drought reservoirs (CDM + DC + Reop + Res)	✓	✓	✓	✓
E) Add drought reservoirs only (CDM + Res)	✓			✓

FIGURE 2.6. Required Institutional Coordination for Implementation and Estimated Costs for Each Drought Management Strategy

	SEDAPAL	ENEL	SUNASS	ANA	Osingermin	Public	Costs $US, millions
A) Current drought management (CDM)	2	1	1	1	1	1	+0
B) Add drought conservation (CDM + DC)	2	1	2	3	1	3	+3
C) Add reservoir reoperations (CDM + DC + Reop)	3	4	3	2	4	3	+8
D) Add drought reservoirs (CDM + DC + Reop + Res)	4	4	4	4	4	3	+137
E) Add drought reservoirs only (CDM + Res)	3	1	4	4	1	2	+129

Note: The scoring was done by SEDAPAL.

storage options without the other additional actions to evaluate whether the storage option renders the other actions unnecessary.

Importantly, SEDAPAL cannot decide on a new way of managing its system without consulting with other stakeholders. Major operational changes and new investments requires SEDAPAL to coordinate with other institutions. These institutions and agencies include ENEL, the main national energy company, which co-manages various reservoirs in the SEDAPAL's system's upper catchments; the National Water Agency (ANA), which authorizes the storage of higher volumes and controls environmental flows; the regulator SUNASS, which validates the minimum release volumes for SEDAPAL to recover costs and sets water tariffs; and Osinergmin, the regulatory agency for energy and mining, which needs to approve any change in releases from the ENEL reservoirs. Moreover, SEDAPAL needs to address stakeholder concerns both within the city of Lima and along its system.

Therefore, to provide additional implementation context, we also developed a qualitative measurement of the different strategies' ease of implementation from an institutional perspective. Specifically, we characterized the level of engagement that will be required by SEDAPAL using a numeric score of 1 to 4, based on discussions with its representatives. We also report the estimated additional cost of each strategy. Figure 2.6 shows that, for instance, Strategy D requires more internal coordination than the current drought measures, but it still falls mostly under SEDAPAL's control and does not necessarily require intense coordination with ENEL and other institutions. In contrast, Strategy E requires much more institutional coordination and include several actors in addition to SEDAPAL.

2.7 Experimental Design

We developed a straightforward experimental design to evaluate different drought management strategies under plausible futures. Table 2.3 describes the defined combination of hydrological sequences with demand and infrastructure assumptions, and drought management strategies. As shown in the top row (row a), we combine the three historical hydrologies described previously with current demand and infrastructure assumptions for the no drought management strategy plus the 5 strategies (for a total of 6). These simulations serve largely as a baseline establishing how different strategies would perform in the future assuming historical hydrology, current demand, and current infrastructure. We next evaluate the five drought management strategies under increasing demand for three different system configurations (current, current plus near-term system improvements, and current plus near-term and long-term projects) (row b). For the current system and current demand, we also simulate how the system would perform with no drought actions. This yields 63 cases based on historical hydrology.

TABLE 2.3. Summary of the Experiment's Design

Type of hydrology	Hydrology traces	Demand	System configuration	Number of drought management strategies	Parameters
Historical	3 different timings	Current	1 (Current)	6	18 (a)
		Increasing	3 (Current; + Phase 1 + Phase 2)	5	45 (b)
Synthetic	10 traces x 66 drought characteristics	Current	1 (Current)	6	3,960 (c)
		Increasing	3 (Current; + Phase 1 + Phase 2)	5	9,900 (d)
Total number of parameters					13,923 (e)

We then combined 660 different synthetic sequences (66 combinations of frequency changes with 10 random traces) with the same set of system configuration and drought management strategies (rows c and d). In total, we evaluated 13,923 distinct cases (row e).

2.8 Interactive Decision-Support Tool

To analyze and share results from the approximately 5,000 simulations, we developed an interactive decision-support tool (DST). The DST is organized into six parts:

1. Scenario factors and experimental design
2. Simulation results for individual cases
3. Simulation results for baseline drought management across different futures
4. Vulnerability analysis of baseline drought management
5. Effects of new infrastructure and additional drought management strategies
6. Key trade-off analysis

The DST was deployed on the Internet using Tableau Public's visualization software. The final version of the DST is available in English and Spanish.[9]

Versions of the DST were shared regularly among the project team and with SEDAPAL planners and collaborators. Analysis results shown in chapters 3 and 4 are taken directly from the DST.

Notes

1. For more information about WEAP, see http:www.weap21.org.
2. Years represent the hydrological period from September to August and are labeled based on the end month. For example, September 2016–August 2017 are all part of the 2017 hydrological year.
3. There are 25 different inflow points to the model, which are represented by 22 separate hydrological sequences.
4. The method was modified to account for wet years and spatial correlation. The original 2016 method did not account for spatial correlation between inflow points when defining wet and dry years, and we modified the method to account for this issue. Additionally, we introduced the weighting of wet months in order to evaluate the potential for greater hydrologic variability.
5. Using the 15th percentile classifies the 2002-03 and 2007-08 hydrological years as normal, although their annual flows are very close to the dry threshold of 1.33 billion meters cubed.
6. The three Marcas indicate the sequenced construction of the investments: Marca I began in the 1960s, Marca II at the end of the 1990s, and Marca III-V in the 2000s.
7. These reservoirs were aggregated and placed on the schematic after inputs from SEDAPAL. Any inflows and connections to the new reservoirs, as well as their intended purposes and operations, were also added after discussion with SEDAPAL.
8. The proportional increase is calculated based on the storage capacity on the Pacific side only, since the transfer of water from the Atlantic side is capped by the capacity of the Trans-Andean tunnel.
9. English and Spanish versions of the DST can be accessed via https://public.tableau.com/profile/rand4185#!/vizhome/JI610-SEDAPAL_Drought-EN/DST and https://public.tableau.com/profile/rand4185#!/vizhome/JI610-SEDAPAL_Drought-ES/HERRAMIENTA.

Chapter 3 How Does SEDAPAL's Current Drought Management Plan Perform?

We begin the analysis by evaluating how SEDAPAL's current drought management plan would perform across a wide range of plausible futures. This provides information about vulnerabilities, which in term informs an assessment and comparison of needed additional drought management actions.

3.1 Performance under a Repeat of Historical Droughts

We first consider how SEDAPAL's current system and current drought management plan would perform in a future with constant demands and hydrologic conditions similar to those in the past.

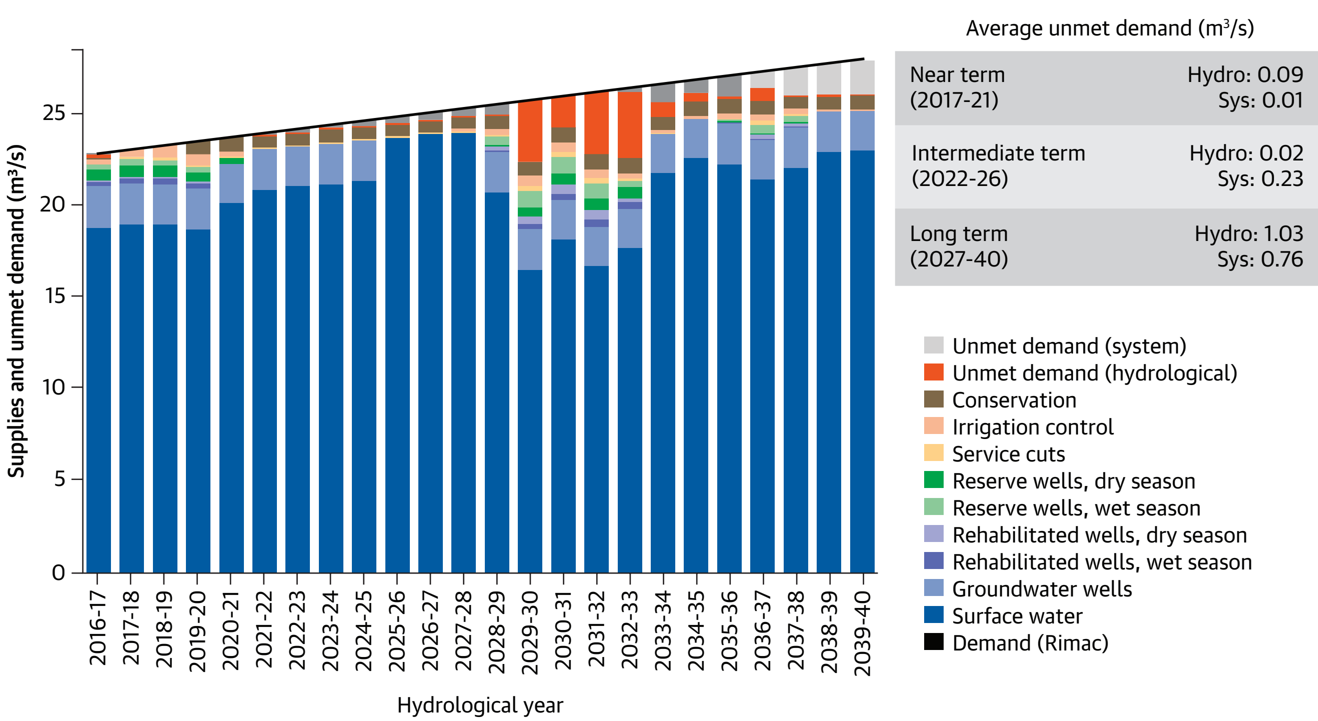
Figure 3.1 shows future outcomes for a historical hydrology (that is, should 1980 drought conditions repeat in 2020): the reservoir storage levels (top), flows of the Rimac River

FIGURE 3.1. Flows, Storage, and Drought Triggers for the Modeling of a Repeat of the 1980 Drought in 2020, Assuming Constant Demand and Constant Demands

(middle), and the initiations of current drought management actions (bottom). For this case, there are two periods of drought, both modeled on historic drought events: the first drought period occurs around 2020, and corresponds to conditions in the early 1980s; the second occurs around 2030, and corresponds to conditions in the early 1990s. During these two periods, total storage declines and, consequently, Rimac River regulated flows drop below the target minimum level of 23 m³/s (the orange shaded portions of the middle panel). The bottom part of the figure shows the different drought actions that are activated to maintain production levels, despite lower flows in the Rimac River. For instance, in this simulation, SEDAPAL cuts irrigation and activates the additional wells in 2021, but no other measures are needed. In 2030, however, all measures are required and activated in a progression.

Figure 3.2 shows projections of the annual average unmet demand for the above simulation and summaries of the hydrological and systemic unmet demand for the near term, intermediate term, and long term. The dark blue shaded bars represent normal levels of surface and groundwater supplies, the red bars show unmet demand driven by low available water, the gray bars show unmet demand driven by other system constraints, and the other colors show the portion of demand met by the various drought management options under the current drought management plan. This figure shows that the current drought management options will result in the almost total avoidance of unmet demand in the 2020 period; the small amount of unmet demand is due to hydrological conditions through 2026: 0.1 m³/s in

FIGURE 3.2. Supplies and Unmet Demand for Repeat Historical Hydrology (If the 1980 Drought Occurred in 2020)



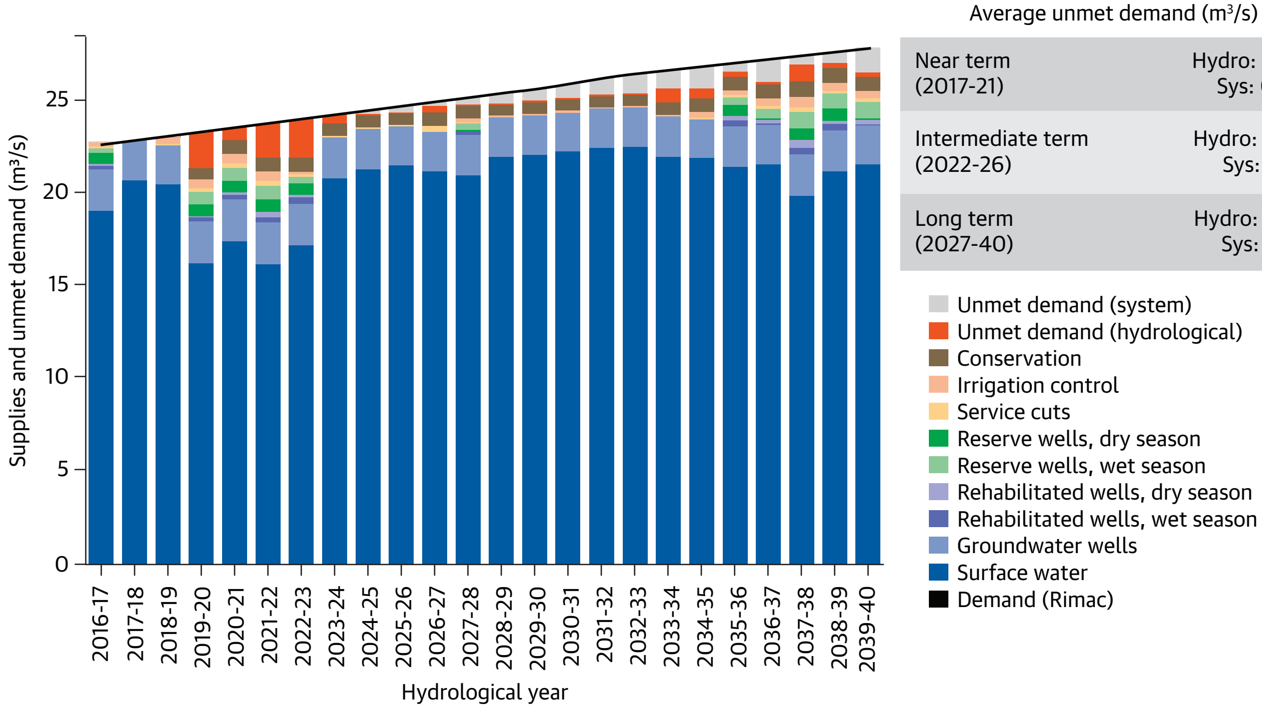
Note: The black line corresponds to the total projected demand. Hydro = hydrologic, sys = system.

the near term and 0.25 in the intermediate term. In the long term, systemic unmet demand begins to accumulate each year due to system constraints. Then the combination of the increasing demands and the strength of the 1990 drought lead to high unmet demands in the 2030 period. For the 2027-40 time period, unmet demand (hydrological and system) averages 1.03 m³/s and 0.76 m³/s, respectively.

If the 1990 drought were to occur in the 2020 time period, significant shortages would occur in the near term (2017-21)—0.58 m³/s (hydrological) and 0.04 m³/s (system)—and in the intermediate term (2022-26)—0.93 m³/s and 0.16 m³/s (figure 3.3). Yet, if the 2004 drought, which was smaller than the 1990 and 2000 droughts, were to be experienced in the 2020s, only a small amount of unmet demand would be experienced in the near and intermediate terms, and this could possibly be eliminated by some minor adjustments in the drought triggers (not shown). Note that in all cases, unmet demand due to the current system's constraints increases over time as demand increases (figure 3.2 and 3.3, gray bars).

These results suggest that the current drought management plan would perform reasonably well in the near term under moderate droughts—such as those in 1980 and 2004—but less so under stronger drought conditions, like that in the 1990s. In the long term—without additional infrastructure—rising demands and all historical droughts would cause large unmet demands.

FIGURE 3.3. Flows, Storage, and Drought Triggers for Repeat Historical Hydrology (If the 1990 Drought Occurred in 2020)



Average unmet demand (m³/s)

Near term (2017-21)	Hydro: 0.58 Sys: 0.04
Intermediate term (2022-26)	Hydro: 0.93 Sys: 0.16
Long term (2027-40)	Hydro: 0.25 Sys: 0.72

Note: The black line corresponds to total demand. Hydro = hydrologic; sys = system.

3.2 Performance under Different Synthetic Drought Conditions

Next, we evaluate how the SEDAPAL system would perform across the larger set of synthetic drought conditions, some of which maintain historical frequencies and magnitudes of dry and wet periods while others increase the frequency and intensities of dry and wet periods. To summarize results over this larger set of runs, we report the average unmet demand in the near/intermediate term (2017-26) for each simulation. From here on, we focus on hydrological unmet demand during the dry years.

Figure 3.4 shows average unmet demand results during dry years for all combinations of frequency and intensity changes evaluated for the current system. Each result represents the average unmet demand over time for 10 different hydrological trials and with increasing demand. For the synthetic sequences with no change in historical hydrologic statistics (upper left corner), average unmet demand between 2017-26 is around 0.77 m^3/s. The upper left quadrant shows scenarios where the frequency of dry and wet months doesn't change (0 percent). As dry years are intensified by 50 percent, unmet demand increases to 2.05 m^3/s. The simulations in which wet years are also wetter—the diagonal results—show that an increased intensity of wet years does not reduce unmet demand during dry periods. This

FIGURE 3.4. Average Unmet Demand of Current SEDAPAL System with the Current Drought Management Plan in Place, for Dry Years in the Near/Intermediate Term (2017-26)

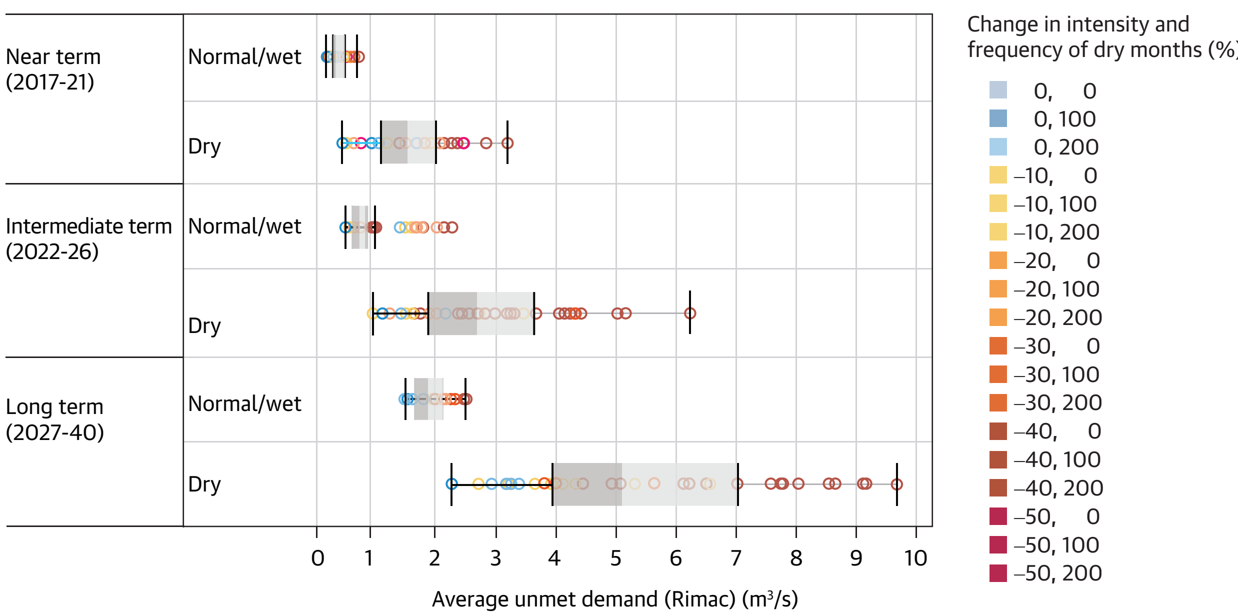
			Wet month intensity change																	
			0%						100%						200%					
Dry month frequency change	Dry month intensity change		Wet month frequency change																	
			0%	10%	20%	30%	40%	50%	0%	10%	20%	30%	40%	50%	0%	10%	20%	30%	40%	50%
0%	0%		0.77																	
	–10%		0.71	0.85																
	–20%	(m^3/s)	0.93		0.94															
	–30%		1.17			1.31														
	–40%		1.45				1.60													
	–50%		2.05					2.20												
100%	0%		1.08						1.17											
	–10%		1.38	1.34					1.40	1.32										
	–20%	(m^3/s)	1.68		1.68				1.63		1.59									
	–30%		2.07			2.10			2.10			2.03								
	–40%		2.64				2.68		2.55				2.58							
	–50%		3.23					3.28	3.16					3.24						
200%	0%		1.92						1.41						1.12					
	–10%		2.30	2.30					1.68	1.71					1.45	1.41				
	–20%	(m^3/s)	2.77		2.77				2.05		2.07				1.67		1.66			
	–30%		3.37			3.36			2.53			2.58			2.11			2.10		
	–40%		3.97				3.96		3.04				3.03		2.58				2.64	
	–50%		4.68					4.67	3.76					3.69	3.07					3.04

result highlights the lack of multi-year storage in SEDAPAL's system that could capture excess flows during wet years and store for use during subsequent dry years.[1]

Figure 3.4 also shows how changing the frequency of dry years and wet years affects unmet demand. The top-left block of results shows that if there are no changes in the frequency of dry or wet periods, unmet demand would range from 0.77 m^3/s to 2.2 m^3/s, depending on how the intensity of dry and wet years would change. The middle panel on the left shows that unmet demand increases by more than 50 percent under a 100 percent increase in the frequency of dry years. This result is consistent across most combinations of dry and wet year intensity. Increasing the dry year intensity even more (bottom left panel) increases unmet demand by about another third to another doubling. For example, under the −10 percent dry year intensity change condition, unmet demand changes from 0.71 m^3/s to 1.38 m^3/s, and then to 2.30 m^3/s for no change, +100 percent frequency of dry years, and +200 percent frequency of dry years, respectively.

Lastly, figure 3.4 shows how increasing the frequency of wet periods concurrently with dry periods affects unmet demand. A comparison of the middle-center panel (100 percent increase in the frequency of dry years; 100 percent increase in the frequency of wet years) with the middle-left panel (100 percent increase in the frequency dry years; no change in frequency of wet years), and with the upper-left panel (no increase in frequency in dry or wet years) shows that increasing the wet year frequency can offset some, but not all of the effect of increasing the frequency of dry years. This effect also applies when the frequency increases are 200 percent (lower-right panel).

FIGURE 3.5. Distribution of Unmet Demand Averaged over Dry and Normal/Wet Years across Different Hydrologies for Different Time Periods under the Current System and Drought Management Plan



Note: In the box plots, the middle gray box represents the middle 50 percent of scores for the scenarios; the dark gray indicates the second quartile; and the light gray indicates the third quartile.

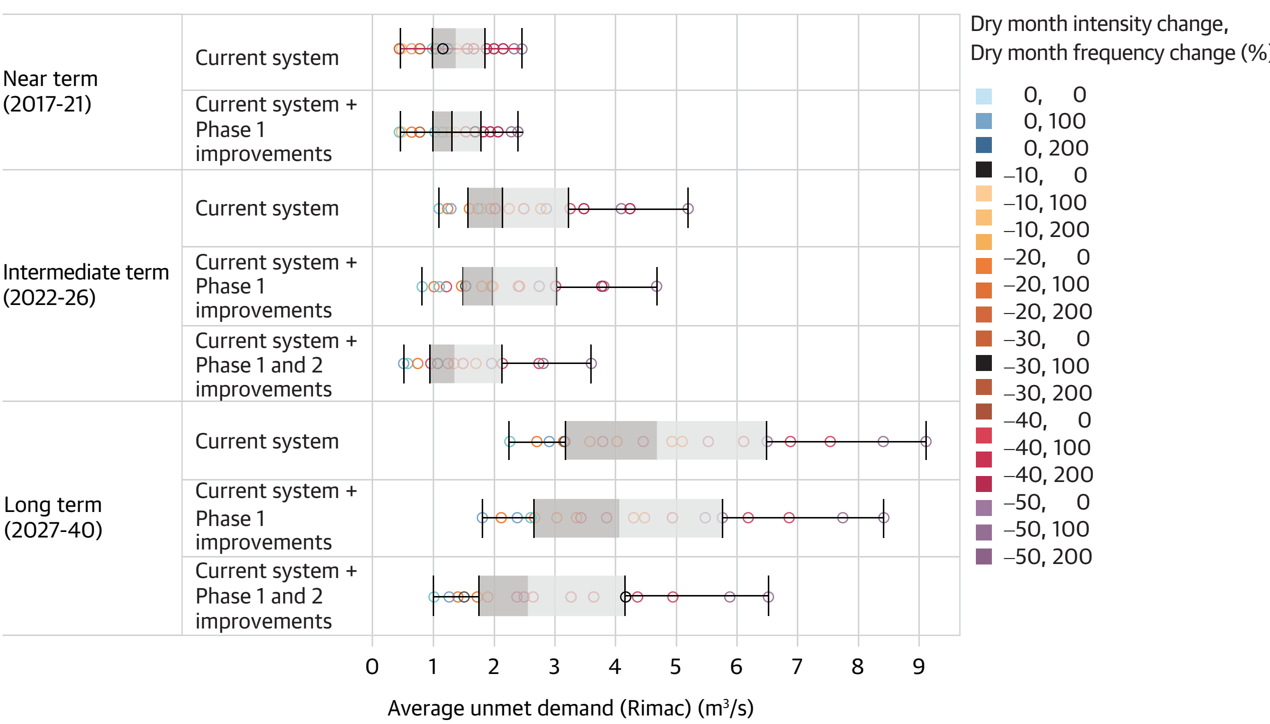
To summarize the range in unmet demands across the different hydrologies, figure 3.5 shows average unmet demand for the near term (2017-21), intermediate term (2022-26), and long term (2027-40). Each circle represents a different simulation and the colors highlight different dry year and wet year intensity changes. Figure 3.5 clearly shows how future unmet demand in the dry years with the current system and current drought management plan in place increases significantly across time. Uncertainty over the future frequency and intensity of droughts leads to a wide range of unmet demands: between 2 m^3/s and 9.5 m^3/s in the long term. Unmet demand increases in the normal/wet years more modestly.

By evaluating current drought management under a wide range of synthetic hydrologic sequences, we find that unmet demand during dry periods would increase significantly over time, with a wide range of outcomes possible. Depending on the future hydrology, the average unmet demand in dry periods could reach as high as 9.5 m^3/s, or be as low as 2 m^3/s.

3.3 Benefits of System Improvements

SEDAPAL's drought management strategy will be strained in the future by continuing demand growth. However, SEDAPAL is aware of this and is already planning and implementing some system improvement projects to increase both its efficiency and its storage capacity, the latter mainly via investments identified in the Master Plan. To better evaluate needed drought

FIGURE 3.6. Distribution of Unmet Demand Across Different Hydrologies for Different Time Periods for the Current System and Current System with Phase 1 and 2 System Improvements



Note: In the box plots, the middle gray box represents the middle 50 percent of scores for the scenarios; the dark gray indicates the second quartile; and the light gray indicates the third quartile.

management augmentations, we estimated unmet demand across all the hydrological scenarios when implementing Phase 1 system improvement projects (for example loss reduction and other efficiency improvement measures, the construction of the Autisha and Casacancha Reservoirs, and the enlargement of the Atarjea WTP) and then Phase 2 system improvements—the Marca II, which includes the Pomacocha Reservoir and the expansion of the Huachipa WTP (figure 3.6). In the near term, only a slight improvement is seen as a result of Phase 1 system improvements, since storage increases (the Autisha and Casacancha Reservoirs) are not yet implemented. In the intermediate term, however, Phase 1 system improvements, by then fully implemented, reduce the unmet demand. During this period, benefits from Phase 2 system improvements are also seen as Marca II investments are gradually brought online between 2023 and 2027. In the long term, the full benefits of both phases of system improvements are realized. The median amount of unmet demand is nearly halved by the implementation of both phases of system improvements. Yet, while addressing systemic unmet demand through system improvements offers some improvement in drought management, the evaluation still shows a significant level of vulnerability in all but the most optimistic futures. In chapter 4, we look at other options for improving the robustness of SEDAPAL's drought management plan.

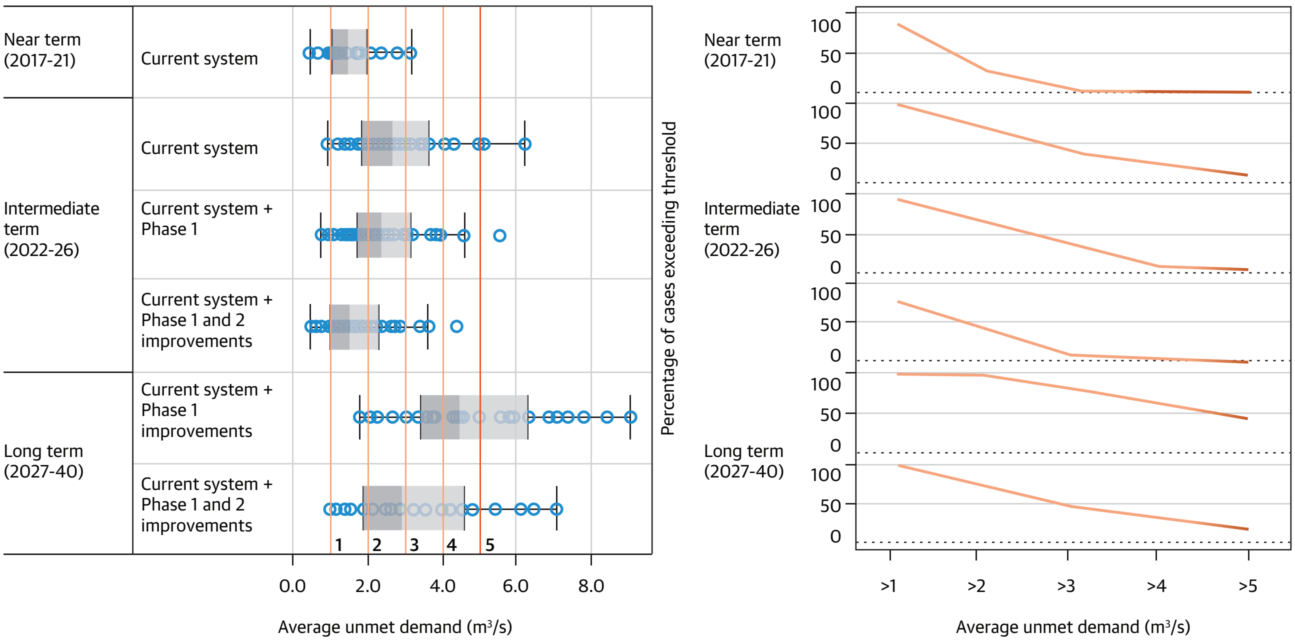
Should both Phase 1 and Phase 2 system improvements be implemented they would play an important role in increasing SEDAPAL's ability to manage droughts across a wide range of futures. However, significant vulnerabilities remain, suggesting that additional drought management actions would be required to increase the robustness of SEDAPAL's current drought management plan.

3.4 SEDAPAL Drought Management Vulnerabilities

To characterize how the SEDAPAL system would perform over time across the wide range of plausible futures considered, we define its vulnerability by comparing the average projected unmet demand during dry years to a set of five vulnerability thresholds: 1 m^3/s to 5 m^3/s of average unmet demand. The 1 m^3/s was chosen to roughly approximate how well the current SEDAPAL system would perform under current demand and drought management practices (the actual number is 0.66 m^3/s).

Figure 3.7 shows the range of estimated unmet demand under the different time periods and levels of system improvement (left panel) and how we summarize the projected range of performance across the large ensemble of hydrologies in terms of the percentage of cases that exceed the five unmet demand thresholds (right panel). The higher the percentage of cases exceeding the threshold, the more vulnerable the strategy is for that threshold. In general, the more cases that exceed the higher unmet demand thresholds the more vulnerable the system is overall. The figure shows that in the near term, the current system is generally not vulnerable with respect to the 3 m^3/s threshold, but it is vulnerable in 75 percent of cases at the 1 m^3/s threshold. Performance is worse in the intermediate term, even with the Phase 2 system improvements. In the long term, the SEDAPAL system with only the Phase 1 system improvements is nearly completely vulnerable at the 1 m^3/s and

FIGURE 3.7. Distribution of Unmet Demand across Futures for Different System Conditions and Time Periods, under the Current Drought Management Plan, and the Corresponding Percentage of Futures that Exceed Different Unmet Demand Thresholds



Note: In the box plots, the middle gray box represents the middle 50 percent of scores for the scenarios; the dark gray indicates the second quartile; and the light gray indicates the third quartile. Unmet demand under the current system and current drought management plan would be 0.66 m^3/s.

2 m^3/s thresholds, and over 50 percent of the cases are vulnerable at the 5 m^3/s threshold. The Phase 2 system improvements, however, reduces vulnerability significantly at all thresholds.

In summary, we find that SEDAPAL's current drought management system is adequate under today's demand and the hydrological conditions of the recent past (section 3.1). When projecting forward, we see potential for modest unmet demand in the near term and more significant unmet demand in the long term (section 3.2). Planned Phase 1 system improvements benefit performance slightly whereas the additional storage that may be brought by the Marca II project is projected to be effective in reducing unmet demand in the long term (section 3.3). By defining and using vulnerability thresholds, we are able to summarize SEDAPAL's system and the performance of its current drought management plan across the range of plausible futures. We find that significant vulnerability remains even with the already initiated and proposed system improvements.

Note

1. As mentioned before, currently their storage and operations allows them to manage one year of failed/low rainfall.

Chapter 4 Improving the Robustness of SEDAPAL's Future Drought Management

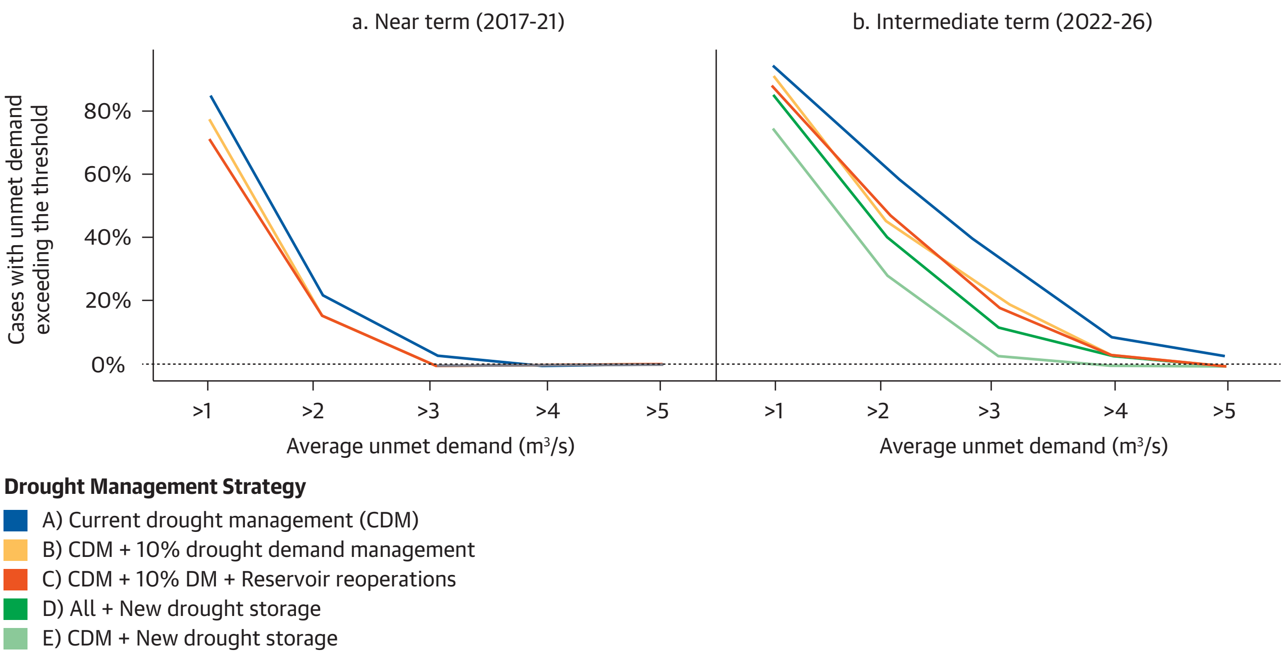
In chapter 3 we showed model projections of future unmet demand across a range of plausible hydrologic conditions for the current drought management strategy under different levels of system improvements, and we defined vulnerability with respect to different unmet demand thresholds. In this chapter we explore how different additional drought management options could reduce vulnerabilities and thus improve robustness.

We define robustness in terms of the range of plausible futures for which a SEDAPAL drought management strategy is not vulnerable—that is would not lead to high unmet demand. To connect to the analysis of vulnerabilities, we first report the percentage of cases that would lead to high unmet demand for the 5 thresholds introduced in chapter 3 (sections 4.1 and 4.2). Next, we characterize the uncertain conditions to which a strategy is robust by identifying the cases in which the average unmet demand is below a given threshold (section 4.3). Lastly, when considering other aspects of augmenting SEDAPAL's drought management strategy-specifically cost and level of coordination with others-we summarize robustness simply by the percent of futures to which a strategy does not exceed the unmet demand thresholds (section 4.4)

4.1 Improved Performance under Additional Options in the Near and Intermediate Term

Figure 4.1 shows how the implementation of additional drought management actions would, in the near and intermediate term, improve the robustness of the current system with Phase 1 system improvements. The left panel shows that in the near term, the additional 10 percent drought demand management (Strategy B) reduces the percent of vulnerable cases at the 1, 2, and 3 m^3/s thresholds of unmet demand. Revising the reservoir operations (Strategy C) has only a modest effect with respect to the 1 m^3/s threshold. In the intermediate term (right panel) the 10 percent drought demand management has an even larger effect, and adding the option for revising reservoir operations helps reduce the vulnerabilities to the higher 3 m^3/s threshold. When the new drought storage is added (Strategy D), vulnerability is all but eliminated at the 3 m^3/s threshold and reduced by more than 50 percent at the 2 m^3/s threshold than with only Strategy C. The Strategy E results, which are less favorable than D, illustrate the importance of adding the non-structural actions included in Strategies B and C, over storage-enhancing alternatives alone. New drought infrastructure alone will not yield all the expected benefits in unmet demand elimination. Like the reservoirs in the Phase 1 system improvement, these new drought reservoirs do not affect results in the near term (2017-21) as they would not come online until 2022, as at the moment no technical, feasibility, or financial study has been conducted.

FIGURE 4.1. Percentage of Cases in the Near and Intermediate Term Where Unmet Demand Exceeds the Five Unmet Demand Thresholds under SEDAPAL's Five Drought Management Strategies (Current System with Phase 1 System Improvements)

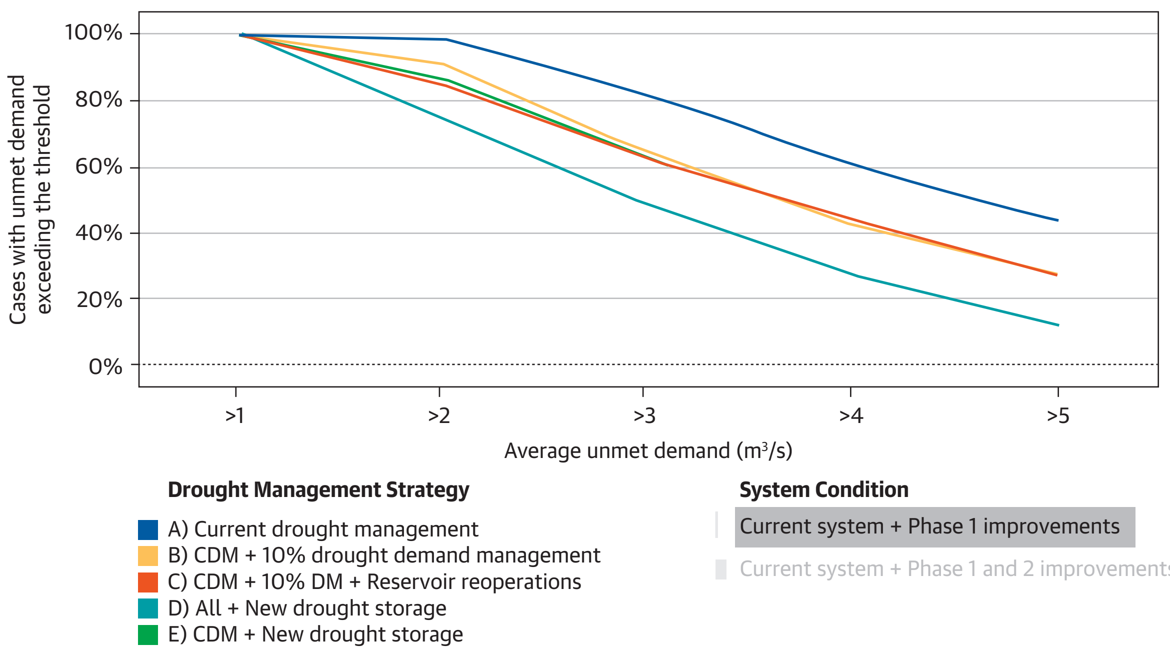


4.2 Improved Performance under Additional Options in the Long Term

In the long term, the impacts of the improved drought management actions are greater. Under the current system with Phase 1 improvements (figure 4.2), adding the 10 percent drought demand management (Strategy B) improves robustness for all but the 1 m^3/s threshold. Strategy C shows a slight improvement in performance for the 2 m^3/s threshold, which is further improved with new drought storage (Strategy D)—it halves the percentage of cases with high unmet demand. Interestingly, Strategy E, which adds extra storage without the 10 percent demand management or reservoir reoperations, yields the same robustness as Strategy C.

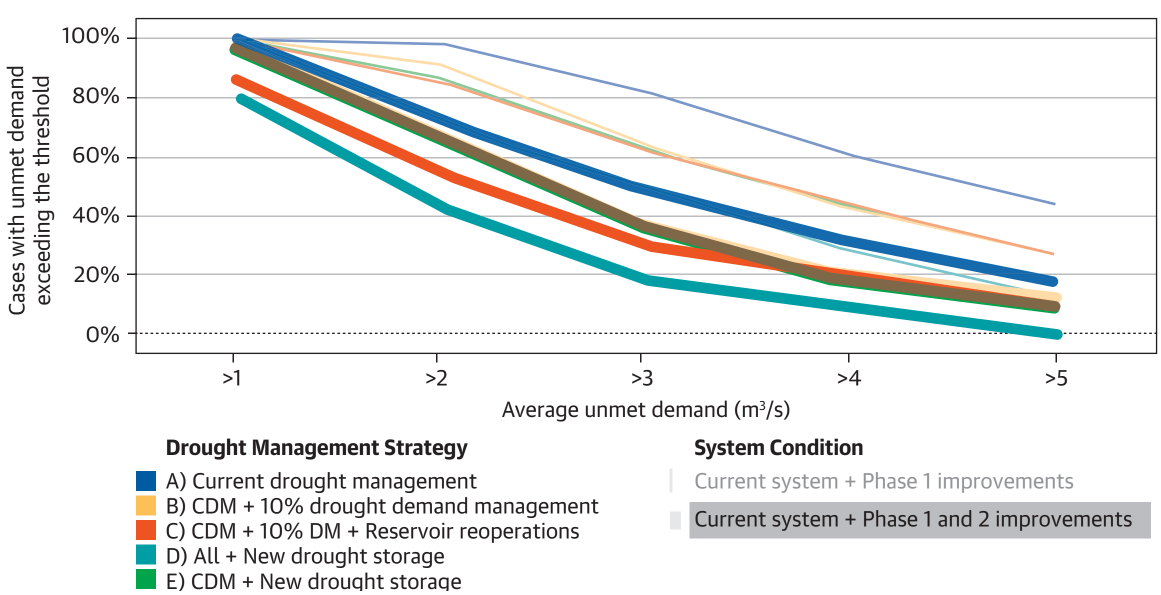
With the current system plus Phase 1 and 2 improvements (figure 4.3), the revision of the reservoir operations has a much greater effect (Strategy C). This is because there is more storage with these system improvements and the benefits from fine-tuning operations becomes greater. As a result, the strategy that includes the new drought storage without the demand management or reoperations (Strategy E) performs relatively poorly, similar to Strategy B. However, Strategy D still improves robustness and continues to halve the percentage of cases with high unmet demand. This shows that even with all the Master Plan's prioritized system improvements in place, and if previously softer measures like system reoperation have been implemented, additional storage remains beneficial for managing droughts.

FIGURE 4.2. Percentage of Cases in the Long Term (2017-40) with Average Unmet Demand Larger Than Each of Five Thresholds for Near-Term and Long-Term Drought Measures (Current System with Phase 1 Improvements Highlighted)



Note: Results for strategies C and E are the same and thus their lines are overlapping in this figure.

FIGURE 4.3. Percentage of Cases in the Long Term (2017-40) with Average Unmet Demand Larger Than Each of Five Thresholds for Near-Term and Long-Term Drought Measures (Current System with Phase 1 and Phase 2 System Improvements Highlighted)



4.3 Characterizing Improved Robustness

This section elaborates on the findings of section 4.2 by defining the hydrologic conditions to which the different system configurations and drought management strategies are robust. We define robustness with respect to the unmet demand thresholds defined above. A strategy is robust to a specified level (for example 3m³/s) for all futures in which the average unmet demand is less than the associated unmet demand threshold (for example <= 3 m³/s). Figures 4.4 and 4.5, for example, show for each combination of hydrologic parameter (see figure 3.4) how robust the current system plus near-term improvements is in terms of meeting the five threshold levels in the intermediate term and long term. The dark green boxes indicate hydrologic conditions in which the strategy meets robustness level 1—that is the average shortages are below the 1 m³/s threshold in each of the futures represented by a dark green box. Figure 4.3 shows that in the short term, robustness level 1 occurs when there are no frequency changes in dry months, unless also compensated for by higher frequencies of wetter months. Lower robustness levels (levels 2-4) are seen when dry month frequencies increase, coupled by increases in dry month intensity. Figure 4.5 shows that in the long term, with the current drought management strategy, the robustness measure is greater than 2 m³/s under any hydrologic conditions different than current ones (upper-left square), even if Phase 1 is implemented.

FIGURE 4.4. Robustness Map for the Near Term, with Current System Plus Phase 1 System Improvements and Current Drought Management Strategies

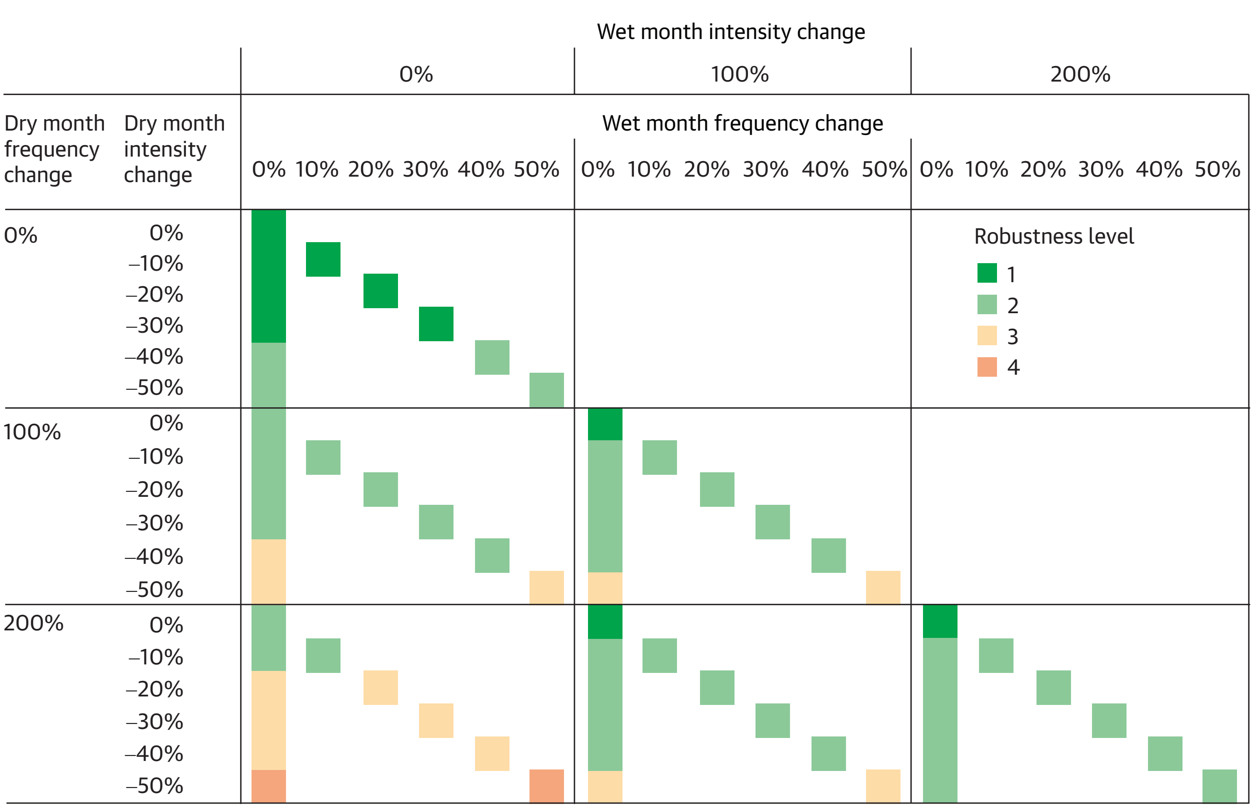


FIGURE 4.5. Robustness Map for the Long Term (2027-40), with Current System Plus Phase 1 Improvements and Current Drought Management Strategies

Figures 4.6 and 4.7 collapse the information in figures 4.4 and 4.5 to show how the implementation of different drought management strategies changes the robustness of the SEDAPAL system in the near term and long term, respectively. Each box in the figures represent one set of hydrologic conditions (average results over 10 trials). The rows show the dry month intensity changes, and the size of the box is proportional to the change in frequency of dry months. There are multiple results for each row to reflect the experimental design that also varies wet year frequencies and intensities. The column in which the boxes are positioned (and their color), indicates their robustness level. The leftmost results are the most robust and the rightmost results are the least robust. Figure 4.6 shows how, for the near term, moving from Strategy A to Strategy B and then to C shifts more cases to the left (more robust), with those corresponding to the lesser changes in dry month intensity being the most robust. The figure also shows that the lower robustness results tend to have higher dry month frequency changes (that is, larger boxes). Under Strategy C, almost all results that correspond to a drying of 40 percent or less are robust to the 2 m^3/s level, whereas results for 50 percent drying are robust to the 3 m^3/s level.

Figure 4.7 then shows the same type of results for the long term (2027-40). This graphic shows drought management under the current system plus Phase 1 improvements as a

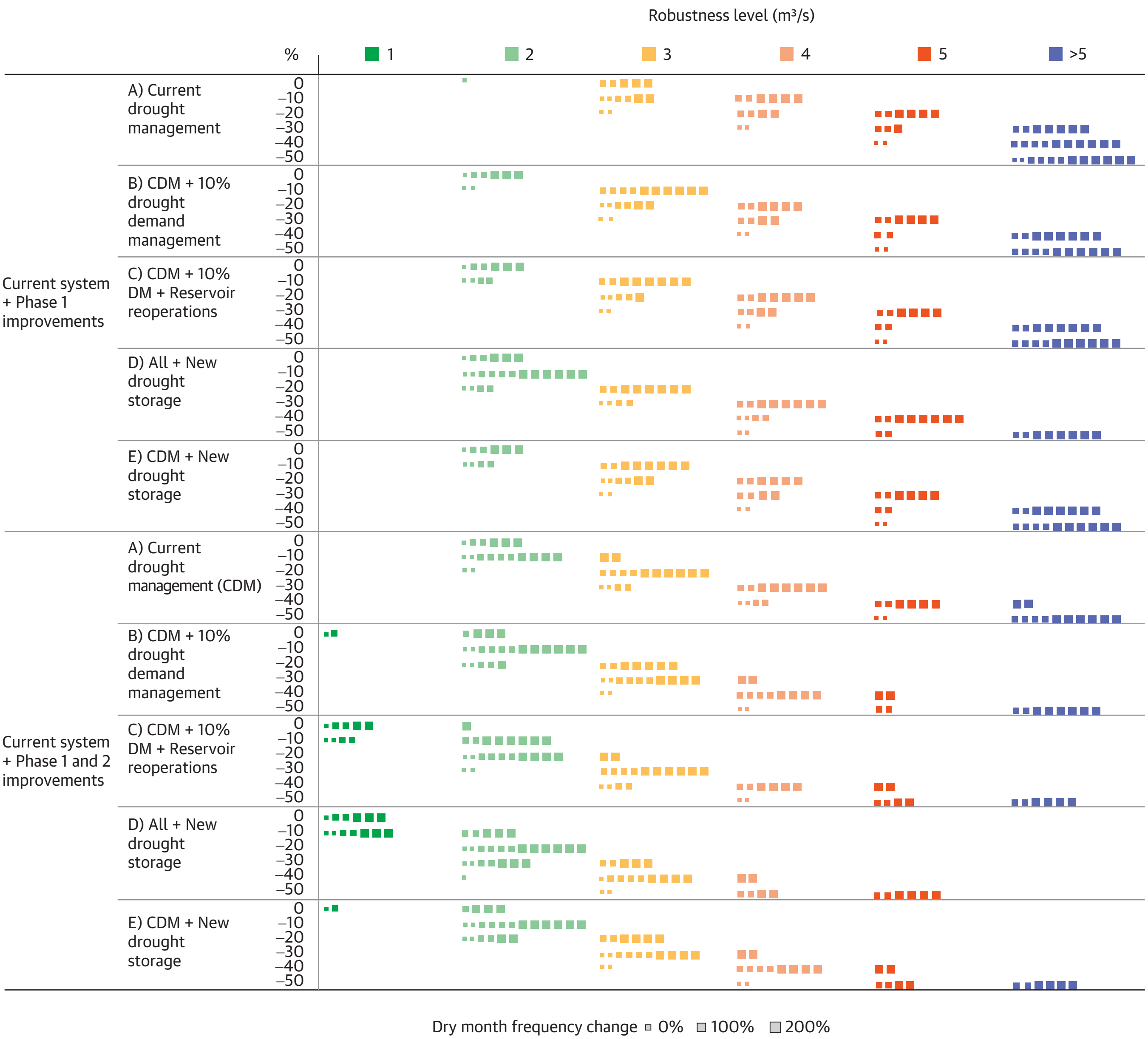
FIGURE 4.6. Consolidated Robustness Map Showing the Level of Robustness in the Near Term (2017-21) for the Current System Plus Phase 1 Improvements and Three Drought Management Strategies; Percentage Changes along the Vertical Axis Refer to Dry Year Precipitation Only

Note: The rows show the dry month intensity changes, and the size of the box is proportional to the change in frequency of dry months. There are multiple results for each row to reflect the experimental design that also varies wet year frequencies and intensities. The red circles and arrow show an example of how Strategy B increases the robustness of the current drought management plan: under B the system becomes robust to the 1 m^3/s level for some hydrologies that under the current drought management plan would have led to a 2 m^3/s unmet demand.

baseline (top row). The figure first shows the dramatic improvement in robustness by implementing the long term system improvements. Note the shift of the colored boxes to the left of the figure. The figure shows that without the Phase 2 infrastructure improvements, the SEDAPAL drought management system is not fully robust under the lower robustness thresholds—there are still many futures in which high unmet demand would result. With the Phase 2 system improvements, however, greater improvements are seen across the drought management strategies. For example, under Strategy D, without Phase 2 implementation, all futures in which drying does not exceed 10 percent, are robust to level 2, but the system is never robust the level 1. Yet, with Phase 2, Strategy D is robust to the at level 1 under no changes in hydrology and robust to level 2 for most futures in which drying does not exceed 20 percent. Strategy E does not add robustness to the lower thresholds even if both Phase 1 and Phase 2 system improvements were implemented.

The results described in this section show the increased robustness that could be achieved through the augmentation of SEDAPAL's drought management plan in conjunction with system improvements. In the near and intermediate term, implementing additional drought management in Strategy B would lead to some modest robustness improvements. Almost all hydrologies resulting a 40 percent drying would be managed at the 2 m^3/s threshold. In the long

FIGURE 4.7. Consolidated Robustness Map Showing the Level of Robustness in the Long Term (2027-40) for the Current System Plus Phase 1 and Phase 2 Improvements and Five Drought Management Strategies



Note: The rows show the dry month intensity changes, and the size of the colored box is proportional to the change in frequency of dry months. There are multiple results for each row to reflect the experimental design that also varies by wet year frequencies and intensities.

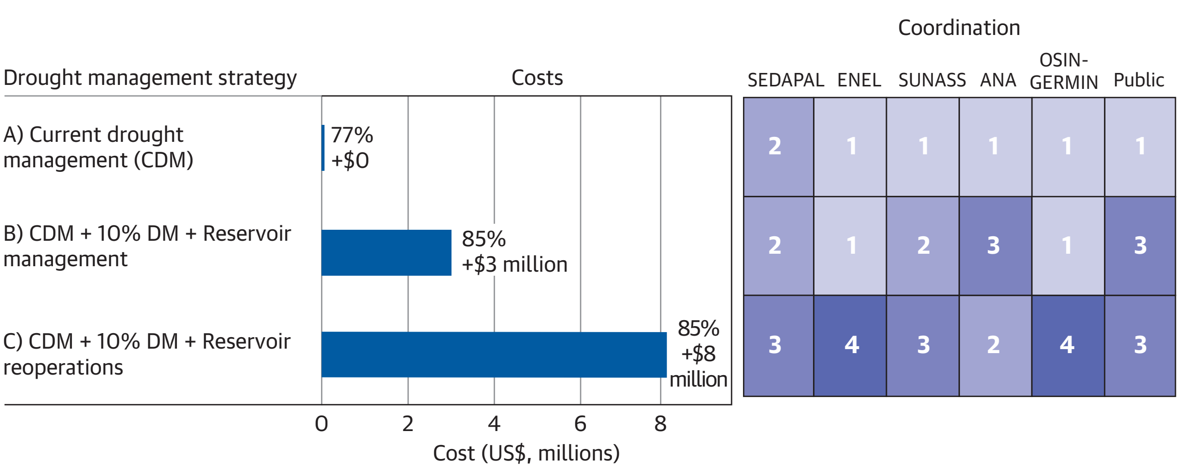
term, the implementation of Phase 1 and Phase 2 system improvements, along with the implementation of Strategy C, Strategy C shows significant robustness improvements—outcomes under current climate conditions would be robust to the more stringent 1 m³/s threshold even if dry months became more frequent, while nearly all hydrologies through a 20 percent drying would be robust at the 2 m³/s threshold. Implementation of Strategy D is required to improve the robustness for futures with a 30 percent drying at the 2 m³/s threshold.

4.4 Trade-Offs

Improving SEDAPAL's ability to manage drought through system improvements and new drought management actions will require potentially large expenditures and significant coordination with other agencies and the public. In this section, we evaluate the cost and coordination trade-offs when improving the robustness of SEDAPAL's drought management plan. The level of robustness desired by SEDAPAL is not determined at this time. Therefore, to highlight the performance differences across the drought management strategies, we show results for robustness level 2 (2 m^3/s unmet demand threshold). This looser threshold of unmet demand could be appropriate if SEDAPAL anticipates a lower projected demand than is evaluated in this study. A more stringent threshold level would show lower robustness across all the strategies, and these results can be reviewed using the interactive decision support tool described in section 2.8.

Figure 4.8 highlights the costs (left x-axis) and additional coordination (in terms of a qualitative score on the ease of implementation, from an institutional perspective) required to implement the three drought management strategies (A, B, and C) that would be available in the near term. The level of robustness is indicated by the color of the bars on the left, in terms of the percentage of cases robust up to level 2 (2 m^3/s unmet demand threshold). Note that darker blue indicates a higher level of robustness. The graph shows that in the near term, to increase robustness from 77 percent of cases to 85 percent of cases, SEDAPAL would incur \$3 million in costs and need to increase coordination with the public (moving from a 1 to 3 coordination score) and with SUNASS (moving from a 1 to 4 coordination score). Implementing the additional actions in Strategy C would cost as additional \$5 million and require coordinating heavily with ENEL. No significant robustness improvements are realized in the near term.

FIGURE 4.8. Near-Term (2017-21) Robustness with Costs (Left) and Coordination Levels with Phase 1 System Improvements (Right), with Estimated Costs



Note: The percentage refers to the level of robustness to the 2 m^3/s threshold; \$ refers to the cost of implementing the strategy, in addition to the costs of the current drought management plan.

FIGURE 4.9. Long-Term (2027-40) Robustness and Responsibility with Phase 1 and 2 System Improvements, with Estimated Costs

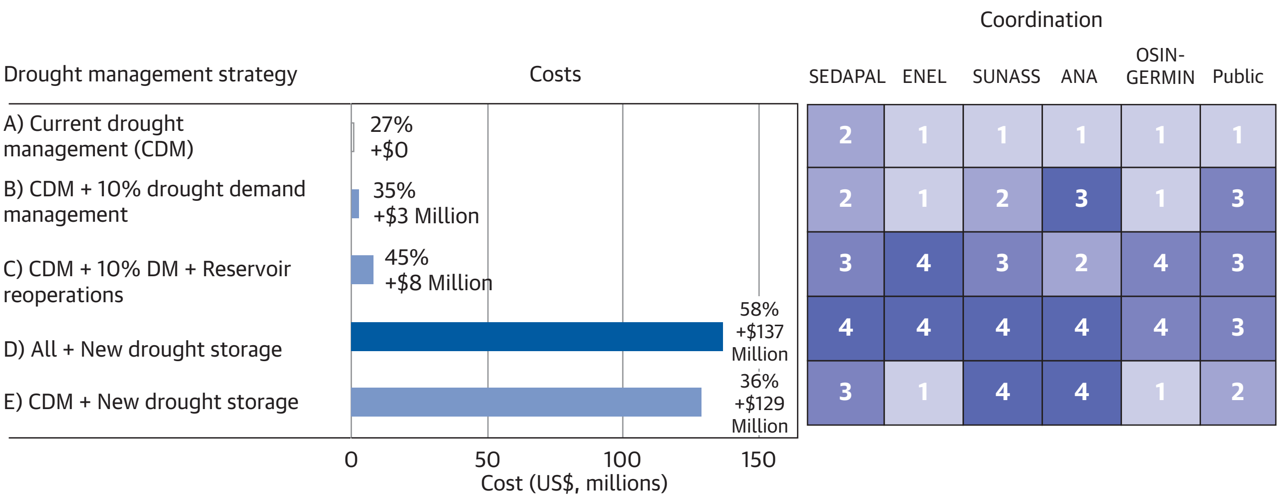
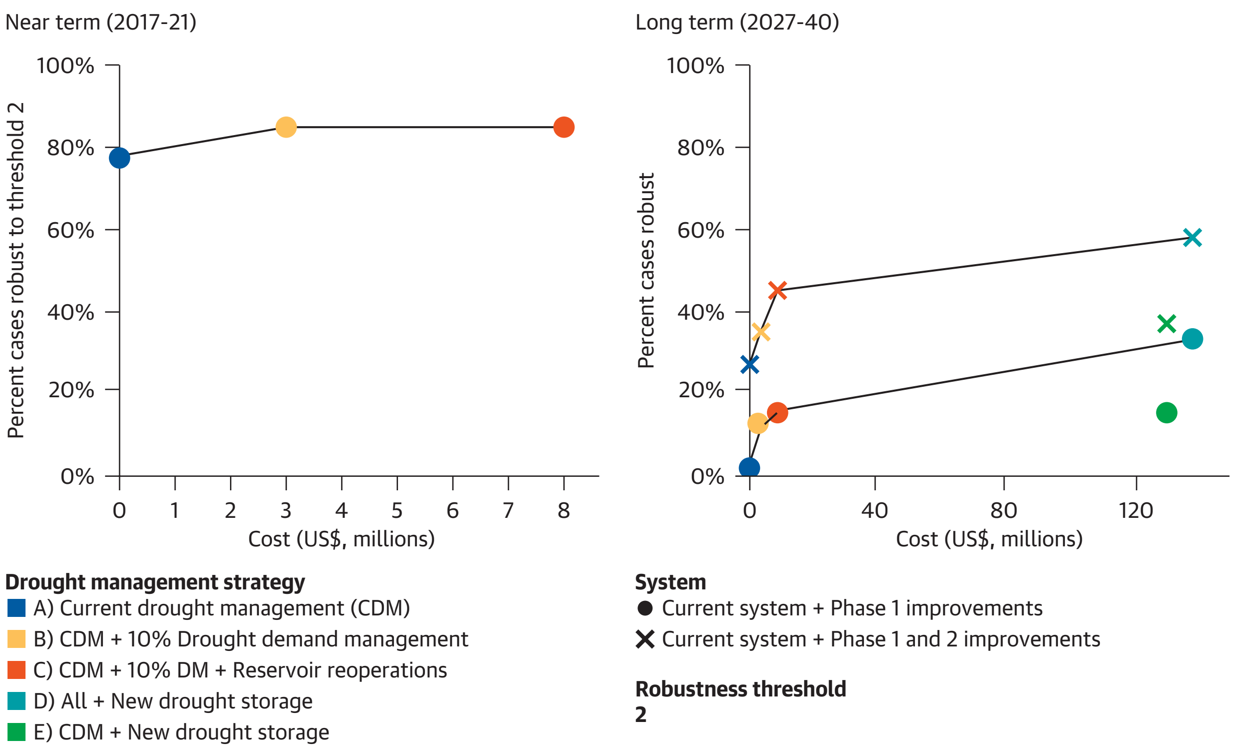


FIGURE 4.10. Robustness and Cost Trade-Offs in the Near Term and Long Term



Note: The x-axis ranges are different for the two panels. M = millions.

In the long term, under the Phase 1 and 2 system improvements, the trade-offs are more favorable when implementing Strategy C. In this case, robustness increases from 35 percent of cases to 45 percent cases for an additional $5 million. The case for implementing Strategy

D rests on the marginal value of increasing the robustness from 45 percent to 58 percent at a cost of $129 million and required level of effort within SEDAPAL.

The left side of figure 4.10 shows the cost and reliability trade-off curve for the near term. This clearly shows that, in the near term, Strategy B appears to be the best choice for SEDAPAL. The right side of figure 4.10 shows the cost and reliability trade-off curves under both system conditions—Phase 1 improvements only (circles) as opposed to Phase 1 and Phase 2 system improvements (x marks) for the long term. For both cases, both Strategy C and Strategy D are clearly better than Strategy E. In the long term, benefits from Strategy C become more pronounced, particularly if Phase 2 improvements are activated, and the main trade-off is that of cost versus robustness level trade-offs between C and D. Chapter 5 proposes an adaptive strategy to help manage this trade-off.

Key findings for the final analysis

- In the long term, Strategy C, with its modest costs and coordination requirements, shows some significant robustness benefits. Determining the need for the additional storage in Strategy D at significant cost and coordination depends on whether the Phase 2 system improvements are implemented and how robust SEDAPAL needs to be. If hydrologic conditions trend toward more significant drying, then these infrastructure improvements become seemingly more justified, even if Phase 2 is implemented.
- Even the implementation of Phase 1 and 2, along with Strategy D, leaves the system vulnerable to extreme scenarios (those that exhibit a 30 percent or more increase in dry month intensity).

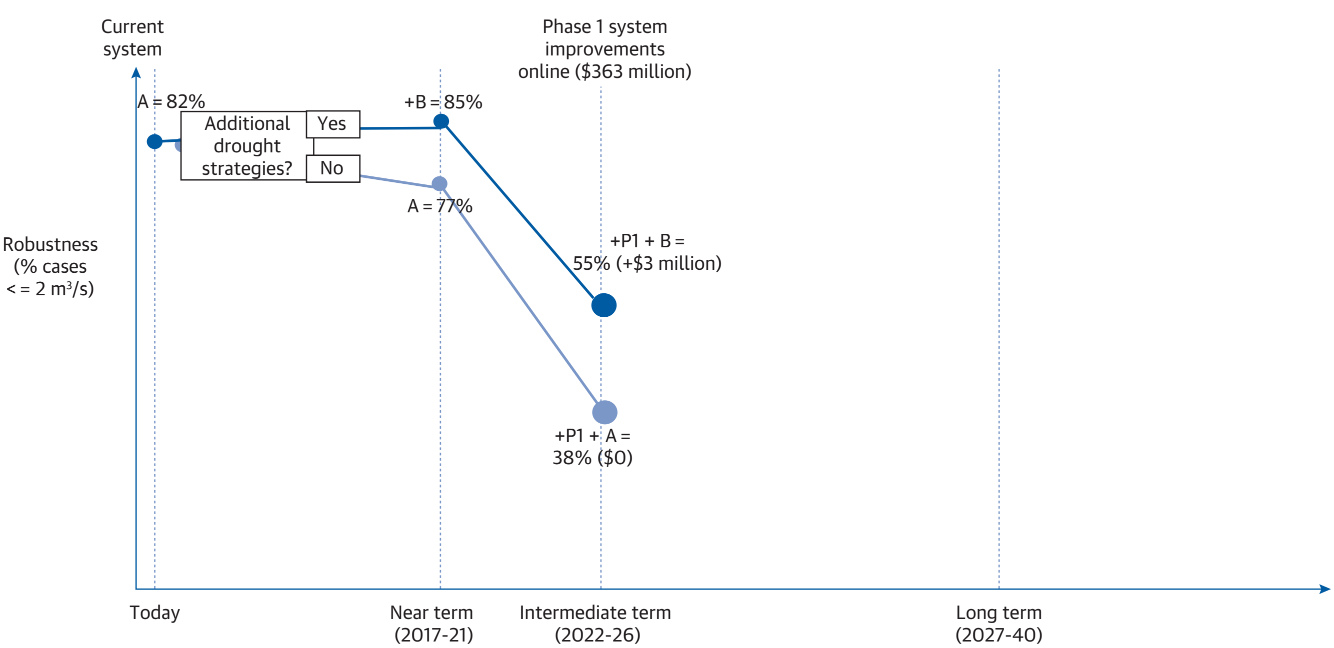
Chapter 5 Staged Implementation of Drought Plan Augmentations

The analysis presented in the previous chapter shows that there are some clear actions that SEDAPAL could take in the near term to improve its drought preparedness, including the Phase 1 system improvements and the drought management options in Strategy B. The system improvements are already underway, and the drought options are low cost and require mostly institutional coordination.

This chapter presents a phased implementation and robustness improvement plan over time, both with and without the development of long term infrastructure improvement. Figure 5.1 shows a schematic of how SEDAPAL might stage the implementation of a drought plan prior to implementing Phase 2 system improvements (that is the Marca II project and Huachipa WTP). The figure shows that without the implementation of additional drought management strategies (+A), robustness will deteriorate significantly over time: from 82 percent of cases today to 77 percent cases in the near term, and to only 38 percent of cases in the intermediate term, using the 2 m^3/s robustness threshold. With the near term implementation of Strategy B's drought conservation, however, robustness significantly improves in the near term and intermediate term to 85 percent and 55 percent, respectively.

Figure 5.2 shows how implementation of additional options benefits robustness in the long term. The lower set of lines show the improvements from additional drought

FIGURE 5.1. Phased Implementation Plan and Qualitative Robustness Trends without Phase 2 System Improvements in the Near Term and Intermediate Term



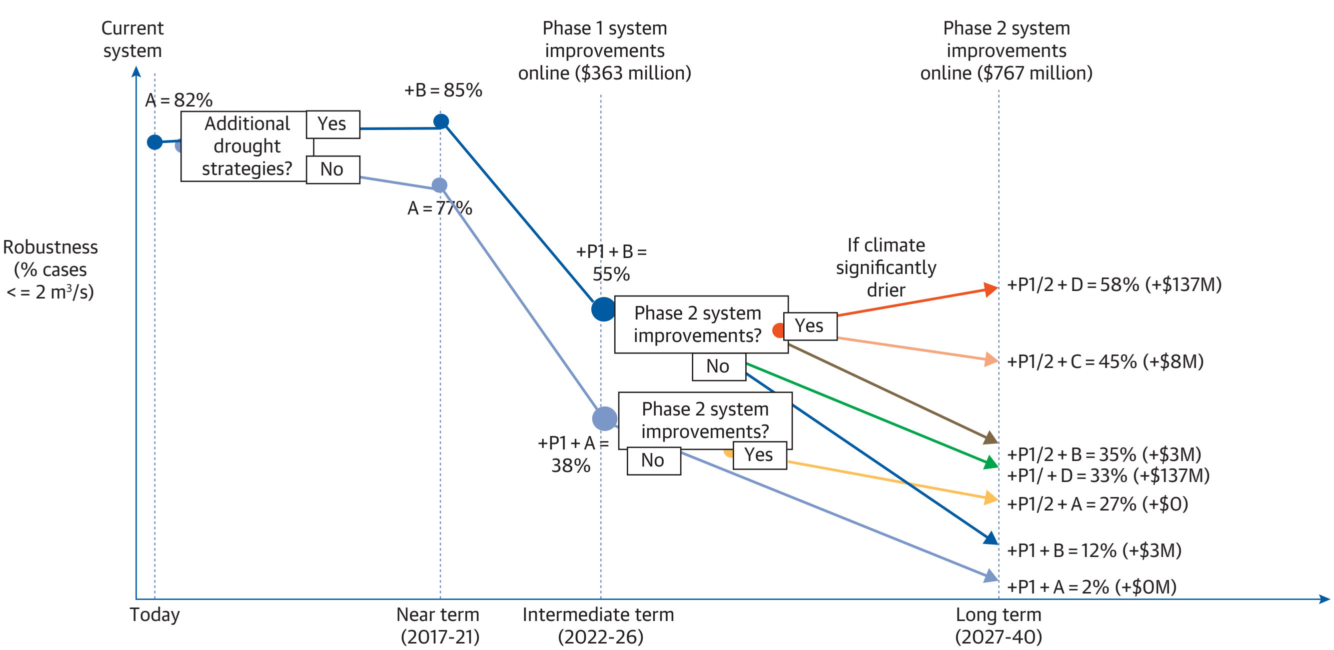
Note: The higher the robustness percentage, the better the performance of the system. P1 = Phase 1 system improvements.

management actions without the Phase 2 system investments. The additional options in Strategy B would increase robustness from 2 percent to 12 percent. Additional drought storage (Strategy D) would improve robustness even more—to 33 percent.

Figure 5.2 also clearly shows how much more beneficial the tested drought management actions would be with the Marca II investments (in the Phase 2 system improvements). While these Phase 2 improvements cost approximately $767 million, this analysis highlights the benefits that this investment would have to the other, less infrastructure-intensive drought management actions. Specifically, these investments increase the robustness of the current drought management plan (Strategy A) from 2 percent to 27 percent, and the robustness of Strategy B from 12 percent to 35 percent. The reservoir reoperations in Strategy C becomes much more beneficial with the addition of the Pomacocha Reservoir, leading to a 45 percent robustness in the long term. The implementation of additional drought storage (Strategy D) should receive more evaluation for implementation for the long term, if needed, as it raises robustness further to 58 percent. As currently configured, this option would be beneficial if future droughts strengthen and/or become more frequent, as is consistent with climate models.

Implementing Marca II and its annexes is critical for the ability of SEDAPAL to successfully manage future droughts. However, even with Autisha, Casacancha, Pomacocha, and the extra drought reservoirs, plus the additional water treatment capacity, 42 percent of futures remain vulnerable. While this may seem high, note that these remaining cases are characterized by more extreme hydrologies, where the frequency of dry months triples and their intensity increases by more than 30 percent. For these cases, robustness is only achieved under the

FIGURE 5.2. Phased Implementation Plan and Qualitative Robustness Trends in the Near Term (2017-21) and Intermediate Term (2022-26), Including Cost (without Phase 2 System Improvements)



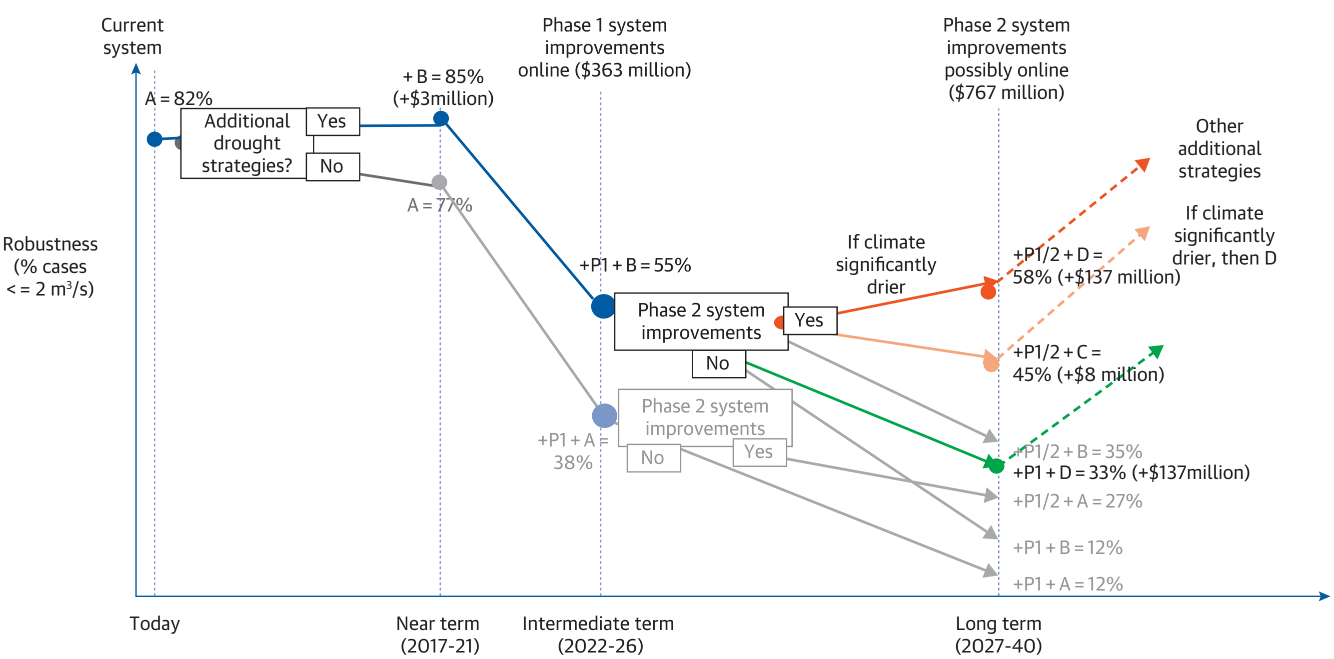
Note: P1 = Phase 1 system improvements; A = Strategy A; B = Strategy B; D = Strategy D.

3 m³/s threshold. While the drought management benefits of Phase 2 are clear from this analysis, Marca II and its annexes are very expensive ($767 million). However, Marca II benefits are not limited to those evaluated in this study. It would also provide needed supply during non-dry years, as it is one of the more cost-effective ways to increase supplies for SEDAPAL to meet future average annual demands (Kalra et al. 2015). Nevertheless, these two studies focused on SEDAPAL's ability to fulfil its mandate. Its social and environmental impacts and feasibility were not evaluated but could be significant and therefore they should be studied further before deciding on Phase 2. Other options currently not considered in SEDAPAL's Master Plan may be available and bring similar benefits with less potential social and environmental impacts.

The analysis therefore suggests that SEDAPAL should consider additional measures, soft or hard, to reduce further the remaining vulnerabilities and hedge against conditions similar to more extreme futures. The remaining 10 Master Plan investments would likely help reduce some of these remaining vulnerabilities. There may also be ways to configure additional drought storage close to Lima that can capture unused flows during the wet months. Preliminary modeling suggests that capturing these flows, which otherwise would end up in the ocean, could significantly improve robustness across the full range of hydrologies. The Autisha Reservoir is partially intended to capture these flows. However, storage close to Lima is difficult due to increased sediment and pollution loads an issue that is difficult to address. Additional work is required to determine the feasibility of this approach. Another measure could be to treat wastewater for reuse.

This analysis suggests that there is a mostly clear path forward for SEDAPAL to improve the robustness of its drought management plan (figure 5.3):

FIGURE 5.3. Recommended Drought Management Augmentation Implementation Plan for SEDAPAL



Note: Gray text represents actions the study does not recommend.

1. Complete Phase 1 system improvements.
2. In the near term (2017-21), prepare to implement additional drought conservation measures (Strategy B).
3. Begin evaluation of drought storage for possible implementation in the intermediate term (2022-27) (Strategy D).
4. Continue to evaluate the feasibility of Pomacocha and Marca II investments (Phase 2 system improvements).
5. If Marca II is deemed feasible, then evaluate the system operations to best take advantage of existing storage, plus the new Marca II reservoir, Pomacocha (Strategy C), and eventually implement new drought storage. If Marca II is not deemed feasible, implement Strategy D, then remain aware that the new reservoirs would only compensate for the absence of Marca II during drought years. Therefore, additional system improvements should be considered, either taken from the Master Plan or new solutions.
6. Remain aware that this set of strategies does not fully eliminate the system vulnerabilities to drought and explore opportunities for further system improvements. Even if Phase 2 and Strategy D were implemented, the system would remain vulnerable to a two-fold increase in dry month frequency and a 40 percent increase in their intensity.

Chapter 6 Conclusions, Limitations, and Recommendations

Prior to this study, SEDAPAL's drought plan had only been tested and evaluated based on historical conditions. Indeed, the plan performed adequately during recent drought conditions. However, SEDAPAL planners did not know how it would perform under future demand increases and changing drought characteristics. The analysis for this study highlights both the effect of longer-term trends on the ability of the drought plan to perform and the vulnerability of the drought plan to changes in the frequency and intensity of droughts. The analysis then quantifies the relative value of the three types of improvements. While the order of priority is unsurprising, the analysis reveals the conditions in which they will be insufficient, which could provide important guidance for future development drought management planning and additional long term infrastructure investments. In addition, the participatory nature of the analysis should help promote uptake by SEDAPAL of the recommendations and methodology for future analyses.

This study provides a first look at how SEDAPAL's drought management plan could be strengthened over time to accommodate changes in demand and drought conditions. Section 5, in particular, provides the following guide for SEDAPAL:

1. Complete Phase 1 system improvements
2. In the near-term prepare to implement additional drought conservation measures (Strategy B)
3. Begin evaluation of drought storage for possible implementation in the intermediate-term (Strategy D)
4. Continue to evaluate the feasibility of Marca II/Huachipa WTP (Phase 2 system improvements)
5. If Marca II/Huachipa WTP is deemed feasible, then evaluate the system operations to best take advantage of existing storage and Pomacocha (Strategy C), and eventually implement the new drought storage (Strategy D), if still needed
    a. If Marca II/Huachipa WTP is not deemed feasible, implement Strategy D, remaining aware that the new reservoirs would only compensate for the absence of the Pomacocha Reservoir during drought years. Therefore, additional system improvements should be considered, either from the Master Plan, or new solutions, including other system operations.
6. Even if Pomacocha is deemed feasible, explore additional measures to protect SEDAPAL from more extreme droughts. These could/would include the remaining elements of the Master Plan, but also new investments that SEDAPAL is currently exploring, like green infrastructure.

This study takes a conservative approach in evaluating robustness by considering a very wide range of changes in hydrologic conditions, coupled with a middle-of-the-road estimate of demand growth. As such, the drought management strategies explored, even in conjunction with Phase 2 storage system improvements, do not lead to full robustness. There are still many cases in which unmet demand would be higher than is currently experienced during droughts. However, if average annual demand were lower, robustness would improve.

There are also other drought management actions that could be beneficial that were not analyzed. For example, our evaluation only tested a few different options. It may be possible to improve operations in a beneficial way even without the additional drought storage in Strategy C or Marca II/Huachipa WTP in the Phase 2 system improvements. An approach for capturing winter flows could also go a long way toward increasing SEDAPAL's ability to manage extended drought conditions.

While this study clearly shows the benefits of Phase 2 infrastructure improvements that include the Pomacocha storage project, the analysis is based on the assumption that the water is available in the Pomacocha source region, in the Yaoli River area, and that diverting the water to the SEDAPAL system will not affect other uses. More detailed studies of the source region, different existing uses, and the project itself is needed before we can be confident of its benefit to SEDAPAL. As such, the adaptive plan described in this study leaves open the possibility that the Pomacocha storage project is not implemented.

Lastly, this study has only just scratched the surface of what will be required to implement drought management improvements. The qualitative scoring of required coordination is only suggestive of the level of coordination required by SEDAPAL, other agencies, and the public. SEDAPAL will clearly be weighing these requirements alongside the technical analysis of unmet demand presented in this study.

Appendix A WEAP Model Improvements and Calibration

Significant changes were made to the original WEAP model (Kalra et al. 2015) in order to represent SEDAPAL's system at a resolution appropriate for modeling drought management options on a shorter time scale.

Specifically, one demand node, Control de Regantes, was added to the WEAP model schematic to help model. Additionally, two groundwater nodes were added: "GW Lima_Atarjea Restriction" and "GWAReturn." The node GW Lima_Atarjea Restriction allows for an annual allotment to be set; note that pumping constraints in WEAP, indicated by transmission links, are averaged to m^3/s, and thus a true annual constraint that allows for variable monthly pumping would be impossible without this node. The node GW Lima_Atarjea Restriction also allows the WEAP model to represent annual increases in groundwater allotment during a dry year, which is another drought response measure available to SEDAPAL. The node GWAReturn acts as an intermediary, taking groundwater flows from GW Lima_Atarjea Restriction and sending them back to the primary storage node, GW Lima_Atarjea. This groundwater storage node was needed because WEAP does not allow for bi-directional groundwater flow between two groundwater nodes.

Given these changes, the model was recalibrated using total reservoir storage, surface and groundwater use, drought management action triggers, and unmet demands as points of comparison. In general, calibration focused on setting priorities and preferences for demands and supplies, thought it did include the addition of some nodes that served mechanical purposes, for example to ensure releases or calculate metrics.

The primary points of calibration were total system storage for the Rimac basin (aggregate storage of all reservoirs providing water to the Rimac basin); flow in Rimac River at the Chosica measuring station; and unmet demand at Sistema Rimac. Simulated total reservoir storage, which is shown in figure A.1, from 2004 to 2009, was compared with observed values during the same range. Note that while observed reservoir storage records were available as recently as 2015, the use of synthetic hydrologies from 2010 to 2016 (used since historical streamflow records were only available until 2009) reduces the utility of direct comparison during these years. Calibrating along this metric helped to ensure that newly enacted reservoir operations, which modified release triggers and goals, reflected historically observed storage values. Note that in 2007 more water is pulled from storage than historical records indicate. During the year 2007, which was considered a drought year, records indicate that SEDAPAL neglected to release enough water to reach their stated target of 130 million cubic meters, which the model is designed to do. Additionally, in historical drought years (see 2004 and 2005 as well), SEDAPAL had released enough water to drop below the 130 million cubic meters target. The model followed these historical rulesets, and it was not designed to account for operational decisions that deviated from this ruleset.

FIGURE A.1. Simulated and Observed Total Rimac System Reservoir Storage (Calibration Period 2004 to 2009)

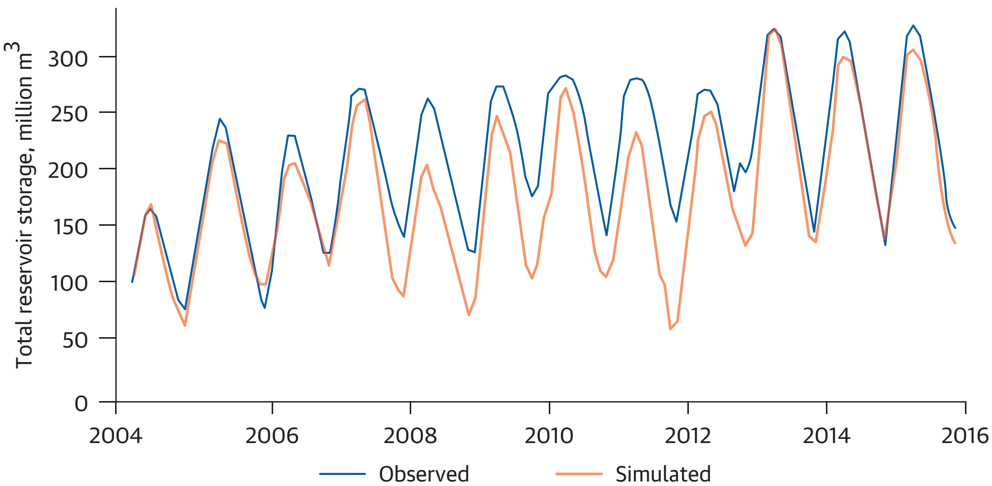
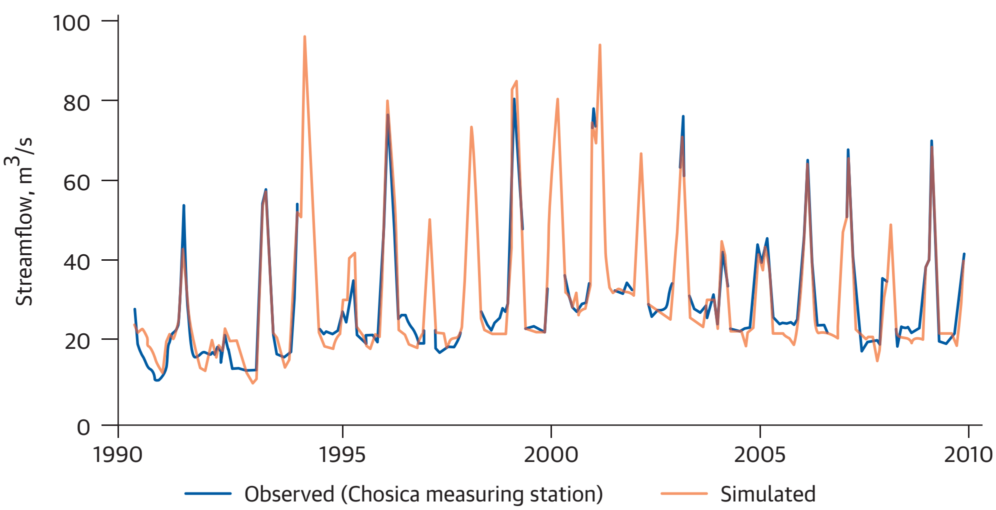


FIGURE A.2. Simulated and Observed Streamflow as Measured at the Chosica Measuring Station (Calibration Period 1990 to 2009)



Flow records for Rio Rimac at the Chosica measuring station from 1990 to 2009 were compared with simulated streamflow to ensure that the model was reflecting the historical availability of surface water supplies to central Lima. Additionally, validating historical streamflow added a second level of verification for reservoir operations, since these operations are largely responsible for dry season streamflow. Unmet demand was compared with information provided by experts at SEDAPAL with knowledge of the system and how it responded to past droughts.

Lastly, simulated quantities of surface and groundwater deliveries to Sistema Rimac were compared with surface and groundwater records from 1999 to 2009 in order to ensure that historic patterns of water use and delivery were being followed by the model. Similarly, expert opinion on historical drought option triggers, in addition to records of additional groundwater use, were used for comparison.

References

Anandhi, Aavudai, Allan Frei, Donald C. Pierson, Elliot M. Schneiderman, Mark S. Zion, David Lounsbury, and Adao H. Matonse. 2011. "Examination of change factor methodologies for climate change impact assessment." *Water Resources Research* 47 (3). doi:10.1029/2010WR009104.

Brown, Casey. 2011. "Decision-Scaling for Robust Planning and Policy under Climate Uncertainty." World Resources Report, Washington, D.C.

Brown, Casey, William Werick, Wendy Leger, and David Fay. 2011. "A Decision-Analytic Approach to Managing Climate Risks: Application to the Upper Great Lakes 1." *Journal of the American Water Resources Association (JAWRA)* 47 (3): 524-534. doi:10.1111/j.1752-1688.2011.00552.x.

Cervigni, Raffaello, Rikard Liden, James E. Neumann, and Kenneth M. Strzepek. 2015. *Enhancing the Climate Resilience of Africa's Infrastructure: The power and water sectors.* Washington, D.C.: World Bank.

De Nys, Erwin, and Nathan L. Engle. 2014. *Living with the semi-arid and proactive drought management in Northeast Brazil : A new perspective.* Washington D.C.: World Bank.

Engle, Nathan L. 2013. "The role of drought preparedness in building and mobilizing adaptive capacity in states and their community water systems." *Climactic Change* 118 (2): 291-306. doi:10.1007/s10584-012-0657-4.

Groves, David G., Jordan R. Fischbach, Evan Bloom, Debra Knopman, and Ryan Keefe. 2013. *Adapting to a Changing Colorado River: Making future water deliveries more reliable through robust management strategies.* Santa Monica, CA: RAND Corporation. https://www.rand.org/pubs/research_reports/RR242.html.

Groves, David G., and Robert J. Lempert. 2007. "A new analytic method for finding policy-relevant scenarios." *Global Environmental Change* 17 (1): 73-85. doi:10.1016/j.gloenvcha.2006.11.006.

Haasnoot, Marjolijn. 2013. *Anticipating Change: Sustainable water policy pathways for an uncertain future.* Enschede: University of Twente.

Hallegatte, Stéphane. 2012. "A Cost Effective Solution to Reduce Disaster Losses in Developing Countries: Hydro-meteorological services, early warning, and evacuation." Policy Research Working Paper 6058, World Bank, Washington, D.C.

Herman, Jonathan D., Harrison B. Zeff, Jonathan R. Lamontagne, Patrick M. Reed, and Gregory W. Characklis. 2016. "Synthetic Drought Scenario Generation to Support Bottom-Up Water Supply Vulnerability Assessments." *Journal of Water Resources Planning and Management* 42 (11). doi:10.1061/(ASCE)WR.1943-5452.0000701.

Hurford, A. 2016. "Accounting for water-, energy- and food-security impacts in developing country water infrastructure decision-making under uncertainty." Doctoral thesis, University College London.

Kalra, Nidhi Rajiv, David G. Groves, Laura Bonzanigo, Edmundo Molina Perez, Cayo Ramos, Brandon Carter, and Iván Rodriguez Cabanillas. 2015. "Robust Decision-Making in the Water Sector: A strategy for implementing Lima's long-term water resources master plan." Policy Research Working Paper 7439, World Bank, Washington D.C.

Lempert, R.J., David G. Groves, Steven W. Popper, and Steven C. Bankes. 2006. "A General, Analytic Method for Generating Robust Strategies and Narrative Scenarios." *Management Science* 52 (4): 514-528. http://www.rand.org/pubs/external_publications/EP20060412.html.

Lempert, Robert J., Steven W. Popper, and Steven C. Bankes. 2013. *Shaping the Next One Hundred Years: New Methods for Quantitative Long-Term Policy Analysis.* Santa Monica, CA: RAND Corporation.

Lempert, Robert J., Steven W. Popper, David G. Groves, Nidhi Kalra, Jordan R. Fischbach, Steven C. Bankes, Benjamin P. Bryant, Myles T. Collins, Klaus Keller, Andrew Hackbarth, Lloyd Dixon, Tom LaTourrette, Robert T. Reville, Jim W. Hall, Christophe Mijere, and David J. McInerney. 2013. *Making Good Decisions Without Predictions.* Santa Monica, CA: RAND Corporation.

Montoya, Moesto, and Enoc Mamani. 2013. "Origin and residence time of water in the Lima aquifer." *Informe Cientifico Tecnologico* 13: 129-135.

National Research Council. 2009. *Informing Decisions in a Changing Climate*. Washington, D.C.: The National Academies Press.

SEDAPAL. 2012. *Memorias Anuales Principales Empresas de Saneamiento de Sudamerica*. Lima, Peru: SEDAPAL. http://www.sedapal.com.pe/c/document_library/get_file?uuid=ff9fd83d-90a4-4b19-a521-fd236426aa8c&groupId=1593749.

———. 2013. “Plan Maestro 2015-2044.” SEDAPAL, Lima, Peru. http://www.sedapal.com.pe/plan-maestro-2015-2044.

———. 2017. “Plan Operativo Institucional.” SEDAPAL, Lima, Peru. http://www.sedapal.com.pe/c/document_library/get_file?uuid=7028230a-452c-4376-ad96-786ac3ab592a&groupId=1593749.

SUNASS (Superintendencia Nacional de Servicios de Saneamiento). 2015. “Informe de propuestas de recarga artificial para el acuífero de Lima.” SUNASS, Lima, Peru.

GWSP
GLOBAL WATER
SECURITY & SANITATION
PARTNERSHIP

WORLD BANK GROUP

W18031