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Strategies for Sustainable Water Supply and Management for Loreto, Baja California Sur, México

A Group Project submitted in partial satisfaction of the requirements for the degree of Master's in Environmental Sciences and Management

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Abstract

Freshwater supplies for Loreto are limited to a single aquifer 30km from town. The aquifer is currently overdrawn due to a combination of factors: inefficiencies in water distribution, domestic overuse, and ineffective management. At the same time, the appealing location on the Sea of Cortez has inspired substantial investments to increase the number of visitors to Loreto. Yet, population growth expected with tourism will further strain already limited freshwater resources. Desalination has been considered the primary solution to meet growing water needs; however, potential negative impacts can offset the benefit of increased water supply. Other alternatives, including those that reduce water demand, must be considered. Therefore, we developed a multi-criteria analytical framework to evaluate both supply and demand alternatives based on criteria relevant to Loreto. Our model results showed that more efficient use of existing supplies--through conservation programs and distribution system upgrades--should be prioritized in Loreto, to make up for the current aquifer overdraft and also minimize the need for additional water supplies in the future. However, successful implementation requires navigation of political and institutional limitations in México. We believe that through a government-funded, community-driven council, Loretanos could influence decision-making in the best interests of the community. By encouraging adoption of combined strategies to prioritize water efficiency measures and to implement a community council to help overcome management challenges, our client, Eco-Alianza de Loreto, A.C., can further its mission to promote sustainable use of natural resources and the environment on behalf of the local community.

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Executive Summary

Loreto is situated in the rugged desert of Baja California Sur (BCS), México, between the Sierra Giganta mountain range and the Gulf of California. The entire population is served by a single aquifer, which is overexploited. To sustain the aquifer and therefore the socioeconomic welfare of the tourism-dependent Loreto community, the amount of groundwater extracted should not exceed the amount replenished. Further, sustainability requires that both current and future population needs be accounted for in water management decisions. The combined notion of *sustainability*—which includes maintenance of the current aquifer level to preserve freshwater quality and supplies, so that the community can capitalize on economic opportunities that unfold over time—is the central motivation for this project. To develop the means for ensuring sustainability, we employ a dynamic multi-criteria analytical (MCA) framework to structure and inform water management decision-making, and then propose an approach for effective implementation in Loreto.

Each year, approximately 60,000 tourists are drawn to Loreto by the diverse flora and fauna of the adjacent Loreto Bay National Park. Although the recent U.S. economic downturn stalled growth, existing and proposed development projects could significantly increase the local population within the foreseeable future.

However, the arid climate severely limits the supply of freshwater available to meet the needs of either the current or future populations. Loreto relies on the San Juan Bautista Londó aquifer 30 km northwest of the town for both agriculture (40%) and urban and domestic use (60%). In this project, we address only the portion under the jurisdiction of local water management in Loreto--urban and domestic use.

The aquifer is being overdrawn, meaning more water is extracted than is replenished. As a result, there are indications that geothermal salts, metals or other contaminants may be degrading water quality in the aquifer. And while potability is not currently affected, continued overdrawing creates a risk to human health and the economic and social well-being of the local community.

Overdrawing for urban and domestic use results from a number of factors, including inefficiency, overuse, ineffective management, and the cultural and institutional situation of water management in México. An estimated 35% of the urban and domestic water pumped from the aquifer is lost due to leaking pipes or other inefficient infrastructure within the distribution system. In addition, per capita use is between 27% and 42% higher than necessary for household purposes. Complicating these concerns, water management in Loreto is characterized by lack of experience and high turnover of decision makers, due to the political and institutional status quo in México. Collectively, these challenges undermine the sustainability required for Loretanos' social and economic well-being—now and in the future.

In order to fully consider the scope of the challenges, we addressed the absence of sustainability in two ways. First, we created a dynamic analytical framework to structure and inform water management decision-making, and to evaluate opportunities to both augment supplies and minimize overuse and inefficiencies. Second, we proposed a means of successfully contending with the political and institutional limitations of water management in Loreto.

To balance the difficulties of limited supply and excessive demand, we selected relevant quantitative and qualitative criteria to evaluate possible solutions within an MCA framework. Our MCA design provides a structured methodology to optimize water management decisions. Equally important, the MCA can be reapplied locally by decision makers, or modified as circumstances change in Loreto.

Using the MCA to account for Loreto's present and future needs, we modeled alternatives for the current population, as well as for two likely population growth scenarios—17,000 and 25,000. We chose nine evaluation criteria relevant to local water management decision-making: investment and operational costs, environmental impacts, energy use, expected yield, confidence in yield, time to implementation, technical sophistication, and scale of infrastructure requirements. We also selected seven alternatives appropriate for the arid, water-limited climate. Five apply to all population scenarios: both low and high conservation programs, infrastructure upgrades, and both small and large desalination plants. Domestic fixtures and aquifer recharge apply only to future population scenarios. We evaluated these alternatives individually and in combined programs against the criteria to identify optimal solutions.

The results of the MCA model show that demand-side measures to reduce the amount of water extracted from the aquifer—specifically conservation programs to reduce per capita use through education or installation of water-efficient fixtures, and infrastructure upgrades to capture water currently lost in the distribution system—should receive precedence at all population levels, whether alone or in combined programs with other alternatives. Our analysis also shows that, while high costs and energy use, as well as potential environmental impacts, generally make desalination a suboptimal option compared to other alternatives, it may eventually be necessary if the population grows beyond the capacity of other programs to compensate for the aquifer overdraft.

These findings provide important guidance to implement more sustainable water resource management for both current and future populations in Loreto. At the same time, our MCA framework can be updated and employed by decision makers in Loreto, as priorities or circumstances shift over time. However, both the successful implementation of the optimal alternatives identified by our analysis, and the effective use of the MCA framework as a decision-making tool depend on successful navigation of the political situation in Loreto.

As a result of the complexities of water management in México, institutional capacity is limited in Loreto. The water manager is appointed by the new municipal president every 3 years, due to the Mexican prohibition of re-election. The high turnover of the role, frequently combined with a lack of professional experience in water management, creates significant discontinuity. However, an opportunity exists to create a government-funded community-based council, called COTAS, to influence and provide continuity to decision-making in Loreto. Since Loretanos have consistently shown a strong interest in civic matters and community sustainability, a COTAS in Loreto could be an effective means of influencing water management decisions in the social, environmental and economic interests of the community.

Through the process of this project, we identified a number of opportunities to address the multi-dimensional water challenges in Loreto and encourage sustainability. Following are the recommendations for our client Eco-Alianza:

Prioritize demand-side measures. Infrastructure upgrades, and conservation measures, such as education and domestic fixtures, should take precedence over new water supply projects.

Implement aggressive conservation programs. Conservation should be a critical component of any water management program in Loreto, and include some combination of education, community outreach, and implementation of water-saving household fixtures.

Create a Loreto COTAS. Formal community involvement can provide both continuity and a sense of ownership over decision-making, and thus inspire more effective water management.

Use the MCA as a decision-making tool. The dynamic MCA framework should be employed by water managers and/or a Loreto COTAS to guide decision-making and justify water management recommendations.

Introduce an environmental review of desalination projects. Benefits of new freshwater supplies should be weighed against the costs to the environment and energy demands on the isolated state energy grid.

Consider renewable energy-powered desalination. Where desalination is necessary, solar-powered desalination should be considered.

Solicit a comprehensive aquifer study. A comprehensive assessment would provide a better basis to determine the sustainable yield of the San Juan Bautista Londó aquifer.

[Re-]Consider water tariffs. Tariffs that reflect actual water use can supplement conservation efforts in Loreto.

Propose means of addressing agriculture overdraft. While agricultural use is outside local jurisdiction, a COTAS could propose measures to track actual water use and promote high use-efficiency technologies.

Through these recommendations, and the underlying analysis that produced them, our project provides Eco-Alianza with the ability to influence the direction of water management in Loreto. In particular, Eco-Alianza can support efforts to reduce water demand by developing and carrying out education programs in conjunction with conservation initiatives. More broadly, by encouraging implementation of the recommended strategies, Eco-Alianza can further its mission to advocate for sustainable use of natural resources and the environment on behalf of the local community.

Introduction

Like other arid areas around the world, Loreto, Baja California Sur (BCS), México, has a limited supply of freshwater. Due to the lack of surface water, the population of 12,000 relies exclusively on groundwater from the San Juan Bautista Londó (SJL) aquifer 30 km from the town. The aquifer is currently overdrawn due to a combination of factors, including water loss in the distribution system, domestic overuse, and ineffective supply management. Expected population growth associated with the tourism industry will exacerbate these freshwater supply concerns. Therefore, in this project, we evaluate strategies to implement sustainable water management practices that address both supply and demand. By focusing on sustainability, our goal is to identify and propose the means by which Loreto can maintain adequate quantity and quality of freshwater for current and future residents, without compromising the community's ability to benefit from the economic opportunities of tourism.

This goal includes two specific objectives: 1) to create a dynamic analytical framework to structure and inform water management decision-making and 2) to propose a means of overcoming the current political and institutional limitations of water management in Loreto. To accomplish the first objective, we evaluate means of both demand control and supply augmentation alternatives for Loreto within a multi criteria-analysis framework (MCA). To employ the MCA, we select nine evaluation criteria relevant to local water management decision-making, and identify seven alternatives to address water supply deficiencies in Loreto. Using a distance-based algorithm, we rank the alternatives across all the criteria to identify optimal solutions within the given constraints. The results of this process allow us to offer recommendations for prioritizing water management strategies. In addition, we design the MCA model to maintain its relevance over time. The resulting flexible and dynamic framework can continue to guide local water management decision-making, based on local priorities and as circumstances change in Loreto.

The second objective is to propose a means to facilitate successful implementation of the management priorities established by the evaluative framework. We first consider the situation in México that contributes to the institutional limitations of water management in Loreto. We then use these insights to determine how management might be improved within existing policies and political constraints, to recommend a solution for Loreto.

Addressing these objectives together allows us to offer both structural and operational recommendations to enable sustainable freshwater management for current and future populations. This comprehensive approach also results in additional recommendations that emerged from our research and analysis for this project.

The rest of this document is organized by section. *Background* introduces Loreto and outlines the significance of this project. *Methods* describes the analytical methodology, including the model design and evaluation of water supply and demand alternatives using the MCA framework. *Results* presents the outcomes produced by the methods. *Water Politics and Management* reviews the political background and opportunities to improve water resources management. *Discussion* holistically synthesizes and contextualizes the findings of the previous sections. This includes discussing means of incorporating water augmentation alternatives in future water resources management planning in Loreto, as well as other factors that need to be taken into account when considering this project. The report then wraps up with our *Recommendations* and final *Conclusion*.

Background

The municipality of Loreto, BCS, México takes its name from the coastal town of Loreto nestled between the Sierra Giganta mountain range and the Gulf of California, also known as the Sea of Cortez. With an area of 4,311 km^2, the municipality has a coastline of 270 km[1] (Figure 1). The population of approximately 12,000[1] is currently concentrated primarily in the town of Loreto, which has steadily transitioned from artisanal fishing to a tourist economy in the past few decades. The local climate is predominantly hot and dry with an average rainfall of approximately 11.5 cm, usually concentrated within a few large storm events during the summer[2].

Figure 1. Map of the Loreto municipality

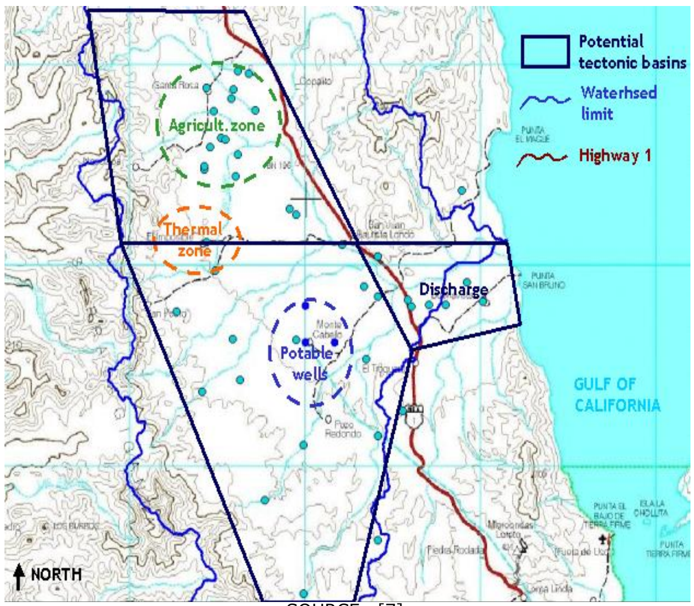
SOURCE: [3]

This extreme climate creates an ecosystem of diverse flora and fauna. In fact, Loreto has been characterized as one of the most biologically diverse regions in all of México[4]. A group of local citizens initiated efforts to protect the area in the 1980's. These efforts continue to this day—in part through our client, Eco-Alianza de Loreto, A.C., whose goal is to promote sustainable governance and the natural environment on behalf of the community. Founded in November 2007, Eco-Alianza's mandate includes advocacy for the preservation and protection of the region's water resources through policy initiatives, community involvement, and public education and outreach. Efforts include building networks with other non-profit organizations, inspiring leadership among local citizens and conducting community outreach. EcoAlianza's interest in preventing further deterioration of the quality and supply of local water resources inspired this project.

Due to its appealing geographic location and the ecological riches of the adjacent Loreto Bay National Marine Park (LBNP), Loreto was targeted in the 1960's by the Mexican National Tourism Promotion Fund, *Fondo Nacional de Fomento al Turismo* (FONATUR) for its tourist development potential[1]. Consequently, the past few decades have seen increasing growth rates as FONATUR and private developers have undertaken aggressive projects to spur economic and population growth. The resulting recent investments—including an international airport, new roads, a hospital, upgraded sewage treatment, and a fully-serviced boat harbor[5]—provide the necessary infrastructure for the municipality to capitalize on the economic opportunities. Currently, 60,000 visitors are drawn to the area each year, primarily by the world-class fishing and diving of the LBNP of the Gulf of California[1], and the number is expected to significantly increase. Although locals are eager to reap the economic benefits of tourism development, there is also increasing interest in sustainable growth. In particular, this interest is spurred by the over-stressed water resources in Loreto and an overall desire to preserve the ecological and cultural integrity of the town.

The arid climate of BCS severely limits freshwater supplies in Loreto. With virtually no surface water, groundwater provides the only reliable source. Due to natural contamination of the local aquifer by heavy metals and other contaminants, Loreto currently depends on the SJL aquifer located 30 km northwest of the city for its freshwater needs[2,6] (Figure 2). This dependence has implications for water supply reliability into the future. Groundwater systems, such as the SJL aquifer, rely on recharge to compensate for water extracted by pumps or lost to natural outflows, in order to maintain a steady water balance. In arid regions, like Loreto, natural replenishment from precipitation and runoff is severely limited. Therefore, unless recharge is augmented by artificial means, extraction must be similarly limited—to sustain the viability of the groundwater supply.

Figure 2. Map of San Juan Bautista Londó aquifer



SOURCE: [7]

The SJL aquifer encompasses an area of 688 km^2[8], and serves the entire municipality of Loreto. Water use from the aquifer consists of 60% urban and domestic, and 40% agriculture[9]. Although the 40% of water used for agriculture makes up a substantial portion of the total volume extracted from the aquifer, only the urban and domestic portion falls under municipal jurisdiction. Therefore, our analysis is restricted to strategies that address urban and domestic water use.

Freshwater for urban and domestic purposes is pumped from two designated wells in the southern portion of the SJL aquifer at an average rate of 110 L/s. This amounts to an annual extraction of 3.47 Mm^3 for urban and domestic use. Of this amount, Loretanos (i.e. residents of Loreto) currently use 513 L/day per capita[1,6], translating into 65% of the pumped water. The remaining 35% is attributed to distribution system losses due to inefficiencies and leakage from pipes[10]. However, even without the significant distribution losses, 513 L/day far exceeds the volume of water necessary for daily life in Loreto, which is estimated to be 375 L/day per person[11]. Together, the overuse and inefficiencies create a high urban and domestic water demand that results in significant aquifer overdrawing* , being the amount by which total withdrawal exceeds recharge. Based on the 60% portion of water extracted from the aquifer, we calculate that urban and domestic use contributes 1.36 Mm^3/year to the most recent aquifer overdraft estimate of 2.26 Mm^3/year[9]†.

In order to maintain the minimum standard of equilibrium required for sustainability of water quality and supply, the amount of water extracted from the SJL aquifer should not exceed the amount replenished by natural or artificial means. Therefore, it is critical to either decrease demand or augment supply, in order to compensate for the 1.36 Mm^3/year overdraft and prevent negative impacts.

Overdrafting of groundwater introduces both natural resource and social concerns. From a natural resource perspective, overdrafting can: induce marine saltwater intrusion that would degrade water quality in the aquifer; increase concentrations of naturally occurring salts, heavy metals, or other contaminants; or result in physical subsidence of the surrounding landscape[12]. Geochemical analysis suggests that geothermal saltwater intrusion may already be occurring in the SJL aquifer[7], indicating an urgent need for intervention to prevent further degradation. From a social perspective, inadequate quantities or inferior quality of potable water can affect the health, quality of life, and economic well-being of Loretanos. These effects will increase in likelihood as the growing population in Loreto increases the overall water demand, further taxing supplies and exacerbating existing overuse and system inefficiencies. Consequently, resource optimization requires consideration of system improvements and efficiency gains to reduce demand, as well as with possibilities for additional water sources to support future population growth.

A 2005 socioeconomic analysis called “Alternative Futures” predicted population growth rates from 3.5% to 14.9% annually in Loreto through 2025[1]. However, as of 2010, the associated

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* In this report, overdrawing and overdrafting is used synonymously.

† Beginning with the Methods section, the term overdraft will only refer to the amount attributed to urban and domestic water use, unless otherwise stated.

population predictions of 30,000 to 240,000 seem improbable to impossible within the next 15 years, in light of the recent U.S. economic downturn, which stalled growth and development in Loreto[13]. Nonetheless, existing and proposed development projects could increase the local population by a significant percentage within a foreseeable timeframe.

For this project, we used population projections based on current developments and project proposals in order to reflect more realistic growth scenarios. Structures left uninhabited by the recent bankruptcy of the Loreto Bay Company[13] can accommodate up to 5,000 additional residents. This provides our analysis with a future population scenario of 17,000 people. Additionally, a recently-approved development project, San Bruno, may bring an additional 8,000 inhabitants to the area. This provides our analysis with a second population scenario of 25,000 people. Though these more likely population scenarios are smaller than those included in "Alternative Futures", the water supply concerns presented within the report persist, given the already overdrawn aquifer.

To accompany "Alternative Futures", Sarté et al. reviewed freshwater supply concerns in the context of Loreto's economic dependence on tourism and the associated incentives for population growth[6]. The report proposed that demand-side measures should receive precedence in water management planning, yet the supply-side option of desalination was the only option considered in any detail. Moreover, the report's recommendations for prioritizing conservation programs and infrastructure upgrades over desalination, for example, were not supported by either a detailed review of water management in México or an analytical framework to compare proposed strategies. Our project fills these gaps.

With Loreto currently facing water shortages and high inefficiencies, tourism-related growth will exacerbate existing conditions and may induce hasty adoption of suboptimal solutions. To mitigate these concerns, we create a dynamic framework to guide water management decision-making in sustainably meeting both current and future population needs. Our minimal objective is to maintain current aquifer levels, in order to avoid further overdrawing that could induce negative environmental and social impacts. This purpose forms the basis of our analysis.

Methods

In the face of near-term population growth as well as dwindling and deteriorating local groundwater supplies, careful water management and planning is essential for sustainability in Loreto. This requires considering a range of possibilities, including supply-side options to augment existing potable sources, and demand-side alternatives to reduce the amount of water drawn from the aquifer. An decision-support framework can facilitate a holistic approach to identifying and planning for implementation of the most appropriate solutions.

Evaluation Criteria

To contend with limited freshwater supplies, potential solutions must be evaluated in the context of the locality of concern. We identified specific factors important to water management in Loreto. The arid *climate* limits both sources of supply and the amount of natural replenishment. *Geography* plays a role in isolating BCS from the main electricity grid in México and from resources necessary to produce electricity. From a *socioeconomic* point of view, the tourism-based economy requires a reliable freshwater supply and limits the range of local technical skills. Inadequate billing and collections, as well as generally limited sources of funding for water projects, result in *financial* constraints. Finally, the *environment* is of significant concern, in particular the LBNP, which is the basis for the local economy and the recent trend toward eco-tourism.

Based on these five factors, we selected nine specific criteria relevant to water management decision-making in Loreto, from a range of possibilities used in similar analyses[14,15,16,17]. These critical evaluative criteria include expected yield, time to implementation, confidence in yield, investment costs, operation and maintenance costs, infrastructure requirements, technical sophistication, energy requirements, and environmental impacts. Brief descriptions of all criterions are in Table 1. For a list of criteria that were initially considered, but not incorporated into the analysis, see Appendix I.

The nine selected criteria have particular relevance, given the circumstances in Loreto. The three yield criteria—expected yield, time to implementation, and confidence in yield—are critical, due to freshwater scarcity, the arid climate, frequency of drought, and the town's economic dependence on a sustained tourism volume. Costs for up-front investments and ongoing operations and maintenance are a significant factor anywhere, but especially in México where money is more difficult to come by and municipal water services are under-funded. Technical sophistication and infrastructure requirements are also important in Loreto, where resources are scarce, and most citizens are employed in service industries, rather than in technical roles.

Energy requirements are another significant concern. BCS is not only natural resource poor, but also the only area of México not connected to the main electricity grid. This means that the state depends entirely on self-generation, and that energy sources for electricity generation must be transported from elsewhere. Most of BCS receives power from the large, gasoline-powered Punta Prieta power plant in La Paz[18]. With high population growth rates in Los Cabos, and steady increases in La Paz, existing capacity may be insufficient to provide electricity for the growing needs of BCS.

The biggest concern for environmental impacts in Loreto is degradation that affects the basis of the local economy—the ecological richness of the LBNP. The LBNP is the primary appeal for visitors to the region, as well as the direct or indirect source of income for most residents. Most residents who do not fish for their primary livelihood: guide visiting fishermen; provide eco-tours; or own or work in hotels, shops, bars or restaurants frequented by tourists. Therefore, to protect the town's culture and economic vibrancy, the environmental impacts on the LBNP in particular must be considered.

Although these nine criteria must be considered in Loreto water management decision-making, they are not all quantifiable in monetary values or similar terms. Some are qualitative in nature. Three are quantitative: expected yield, investment costs, and operation and maintenance costs. The remaining six criteria are qualitative and include time to implementation, energy requirements, confidence in yield, environmental impacts, infrastructure requirements, and technical sophistication. Table 1 lists all nine criteria.

Table 1. Criteria, with value types and descriptions

Criterion	Value Type	Description
Investment Costs	Quantitative	Start up costs, such as the cost of building new infrastructure, excluding the price of land needed for new facilities
Operation and Maintenance Costs	Quantitative	Ongoing costs associated with general maintenance, operation, and/or administration
Expected Yield	Quantitative	The percent of compensation for the aquifer overdraft attributed to urban and domestic water use
Time to Implementation	Qualitative	The amount of time to reach the full expected yield, from the time implementation begins
Energy Requirements	Qualitative	Operational energy requirements, exclusive of operations costs and upstream environmental impacts
Confidence in Yield	Qualitative	Consistency and reliability of supplies or water savings
Environmental Impacts	Qualitative	The direct relative negative impact on the terrestrial and marine environment, excluding aquifer state or upstream impacts of electricity generation
Infrastructure Requirements	Qualitative	Relative amount of new infrastructure and facilities required, including replacement of existing infrastructure
Technical Sophistication	Qualitative	Relative expertise required for operations and maintenance, exclusive of knowledge required for construction or design

Due to this combination of qualitative and quantitative criteria critical to local decision-making, we employed a multi-criteria analysis (MCA) to evaluate water supply and demand options. In addition to providing a structured methodology to guide current water management decisions, the MCA also provides a reproducible framework with the dynamism and flexibility required for ongoing decision-making.

Multi-Criteria Analysis

The MCA has been widely applied in water resources management, as it is uniquely suitable to the inherent complexities and increases the transparency, accountability and rigor of the decision-making process[15]. It provides a framework for ranking or scoring decision options against multiple criteria, using both qualitative and quantitative data within a mathematical model[19]. Additionally, the MCA allows weights to be assigned to the various criteria used in the analysis to represent their relative importance based on given objectives.

For this project in particular, the MCA method fulfills the first part of our project goal by providing a dynamic framework to guide water management decision-making in Loreto. Using the MCA framework, we can compare water management alternatives in a structured and reproducible manner, in order to offer recommendations for priorities based on the situation in Loreto. The framework also supports ongoing water management by allowing local decision makers to: modify inputs as circumstances change or more information becomes available, adjust weights according to shifting objectives, and incorporate the evaluation of additional alternatives when needed[17].

To employ the MCA for this project, we followed a staged process that included:

1) defining factors important to water management in Loreto;
2) determining population scenarios;
3) selecting evaluation criteria that relate performance to objectives;
4) selecting alternatives;
5) generating an evaluation matrix with performance measures for each alternative against each criterion and creating programs of the alternatives;

6) generating sets of criteria weights to reflect decision maker objectives/preferences;
7) running the model and performing a sensitivity analysis; and
8) presenting recommendations from the outcomes.

Based on the MCA algorithm we chose, conducting the analysis included: transforming all performance measures into commensurate units in step 5, and calculating scores, ranking alternatives, and examining ranks to define proposed solutions in step 7[16,19,20].

Population Scenarios

Decision-making in Loreto requires meeting the needs of both current and future populations that might eventuate due to tourism growth. As the population increases, so will the water demand, exacerbating the existing aquifer overdraft, and providing additional challenges and opportunities for local water resources management. Using the likely population growth scenarios identified in the Background section, we evaluated water supply alternatives at three population levels (Table 2).

Table 2. Population scenarios used in the MCA

Population Scenario	Total Population Size
Current Population	12,000
Growth Scenario 1	17,000
Growth Scenario 2	25,000

Criteria Values

To compare and measure the performance of the various alternatives, we first defined the units of measurement for quantitative criteria, and the range of values for qualitative criteria. Of the three quantitative criteria, expected yield was to be measured in percentage of overdraft covered, and investment and operation and maintenance costs were to be estimated in U.S. dollars. The six qualitative criteria—time to yield, confidence in yield, energy requirements, technical requirements, infrastructure requirements, and environmental impacts—were each designated a range of possible values that would be assigned by subjective comparisons against each other. The criteria and their units of measurement are listed in Table 3. A list of simplifying assumptions that were used in estimating and determining criteria values is in Appendix II.

Table 3. Criteria with units of measurement

Criterion	Type	Unit of Measurement
Investment Costs	Quantitative	(U.S. Dollars)
Operation and Maintenance Costs	Quantitative	(U.S. Dollars)
Expected Yield	Quantitative	(Percent of overdraft)
Time to Implementation	Qualitative	(Immediate – Long-term)*
Energy Requirements	Qualitative	(Very Low-Very High)**
Confidence in Yield	Qualitative	(Low-High)***
Environmental Impacts	Qualitative	(Very Low-Very High)
Infrastructure Requirements	Qualitative	(Very Low-Very High)
Technical Sophistication	Qualitative	(Very Low-Very High)

** Immediate, Short Term (~1yr), Medium (1-3yrs), Medium-Long (3-7yrs), Long-term (7+yrs)*
***Very Low, Low, Medium, High, Very High*
**** Low, Medium, High*

After establishing the range of evaluation for each criterion, we then turned to selecting possible means of either reducing the amount of water drawn from the aquifer, or augmenting the amount of water available to meet the needs of the Loreto community.

Water Management Alternatives for Loreto

We identified seven water management alternatives that are both feasible and appropriate for Loreto based on existing conditions. As noted in the Background section, desalination is the presumptive means of solving water supply problems in Loreto, whereas other water management options have not yet been fully explored. To address water demand, we chose means of reducing the amount of water withdrawn from the aquifer for delivery and use. On the supply side, we selected options to augment existing freshwater supplies.

Five of the seven alternatives apply to all population scenarios: both low and high conservation programs, infrastructure upgrades, and both small and large desalination plants. An additional two alternatives—domestic fixtures and managed aquifer recharge—apply only to future population scenarios. The seven total alternatives are listed in Table 4.

Table 4. Alternatives used in current and future population scenarios

Alternatives for Current Population Scenario	Alternatives for Future Population Scenarios
High Conservation	High Conservation
Low Conservation	Low Conservation
Infrastructure Upgrades	Infrastructure Upgrades
Small Desalination	Small Desalination
Large Desalination	Large Desalination
	Domestic Fixtures
	Managed Aquifer Recharge

As described below for each alternative, we established the appropriate quantitative or qualitative criteria values through multiple means. Where appropriate, we conducted a rigorous review of relevant documents, case studies and technical literature. In addition, we used actual data on water use in Loreto, including aquifer statistics, pumping rates and per capita use (see Appendix III).

Water Conservation Programs

Water conservation is an integral part of managing freshwater resources. For regions experiencing population growth, such as Loreto, water conservation can adjust current water use patterns to maximize existing water supplies. Water conservation can be achieved in several ways, varying greatly in terms of complexity, cost, and water savings[21]. For this project, we included two water conservation programs, one that yields a high level and one that yields a low level of water savings.

High Water Conservation

High conservation in this analysis incorporates an extensive ten-year education and outreach program along with financial incentives for the installation of water-efficient domestic fixtures in existing homes. Our goal for the program is per capita reductions from 513 L/day to 375 L/day, a decrease of 27%. In the MCA, we expect a 22% reduction in per capita water usage, which matches the achievement of 80% of the goal of a similar ten-year program in Ashland, Oregon.

Based on the Ashland study, we estimated the total cost for implementing a high conservation program in Loreto to be $247,700. Operations and maintenance costs in this analysis are perpetual recurring costs rather than monies spent over a fixed number of years. Consequently, the total costs of high conservation, which includes both investment and ongoing costs of program operations for the ten-year period, were combined in the investment cost criteria. All criteria values used for high conservation in the MCA model are shown in Table 5. Additional details on this alternative are in Appendix IV.

Table 5. High conservation criteria values

Criterion	Value
(1) Expected Yield	
Current Population	0.36
17,000 scenario	0.24 (0.26*)
25,000 scenario	0.20 (0.22*)
(2) Time to Implementation	L
(3) Confidence in Yield	M
(4) Investment Costs (U.S. $)	247,800
(5) Operation and Maintenance Costs (U.S. $)	0
(6) Technical Sophistication	VL
(7) Environmental Impacts	VL
(8) Energy Requirement	VL
(9) Infrastructure Requirements	VL

*See appendix VIII for specifications on expected yield values in combination with domestic fixtures

Low Water Conservation

The low conservation program value is characterized by a lower level of complexity, cost, and water savings. It only includes a three-year education campaign focused on changing water use habits. In general, such a program reduces water demand by 2-8%[21]. For the MCA, we used the median value of 5%, although this may be on the conservative side for Loreto, given the relatively high current overuse compared to the baseline of other areas that have implemented similar initiatives.

To determine the costs of the low conservation program, we used a single year's cost of the high conservation program, plus an additional 20% investment cost. This was based on the assumption that 10% of the high conservation program would cover the costs of running a shorter and less expansive program in Loreto, but that start-up costs would also be incurred. This calculation established a total cost of $29,700 for the low conservation program, including the cost of ongoing program operations over the three-year period (see Appendix IV for details). The high and low water conservation programs in this analysis are compared in Table 6.

Table 6. Comparison of low and high conservation

Program	Characterization	Water Savings	Investment Cost ($)
Low Conservation	Education Program	5%	$29,700 (for 1-3 years)
High Conservation	Extensive Education Program and Financial Incentives for Domestic Fixtures	22%	$247,700 (for 10 years)

The low conservation program values are different from the high conservation program for only three criteria: time to implementation (less time), investment costs (lower costs), and the expected yield for each of the three population scenarios (lower yields). Table 7 shows all the criteria values used for low conservation in the MCA model.

Table 7. Low conservation criteria values

Criterion	Value
(1) Expected Yield	
Current Population	0.08
17,000 scenario	0.06
25,000 scenario	0.05
(2) Time to Implementation	M
(3) Confidence in Yield	M
(4) Investment Costs (U.S $)	29,700
(5) Operation and Maintenance Costs (U.S. $)	0
(6) Technical Sophistication	VL
(7) Environmental Impacts	VL
(8) Energy Requirement	VL
(9) Infrastructure Requirements	VL

Infrastructure Upgrades

Upgrades and maintenance of water distribution systems are among the most effective methods that can be employed for water conservation[22].Appendix V includes more details on potential gains from demand-side measures that include implementation of conservation programs and infrastructure upgrades.

For this analysis, infrastructure upgrades consist of identifying and repairing leakages, conducting pressure adjustments, and replacing aging infrastructure within the existing urban water distribution system. We were unable to determine exact costs of conducting complete infrastructure upgrades in Loreto, so we extrapolated costs of previous projects in the region. Based on CONAGUA's 2009 investments for water infrastructure projects for the entire state of BCS, we established a per capita investment rate to determine the approximate cost for upgrading existing infrastructure in Loreto. This gave us a cost estimate of $364,700[23]. Operation and maintenance costs were set at zero, as investments in aging infrastructure would not incur additional costs. In fact, upgrades would most likely lower current operations and maintenance costs, by reducing system-wide maintenance requirements. For expected yield, we assumed achievement of 100% efficiency within the distribution system by recapturing the 35% of water currently lost through leaks and inefficiencies. Table 8 shows the complete list of values used for infrastructure upgrades in the MCA model.

Table 8. Infrastructure upgrades criteria values

Criterion	Value
(1) Expected Yield	
Current population	0.90
17,000 scenario	0.62
25,000 scenario	0.50
(2) Time to Implementation	ML
(3) Confidence in Yield	H
(4) Investment Costs (U.S. $)	364,800
(5) Operation and Maintenance Costs (U.S. $)	0
(6) Technical Sophistication	M
(7) Environmental Impacts	M
(8) Energy Requirement	VL
(9) Infrastructure Requirements	L

Saltwater Desalination

Saltwater desalination is a process of stripping salt, minerals, or other components from seawater to produce potable water. Due to Loreto's proximity to the Gulf of California, desalination could provide an unlimited source of water. While the possibility of an unlimited supply is appealing, there are also various downsides associated with desalination. Table 9 below lists some of the advantages and disadvantages. Details on the advantages and disadvantages, as well as a best practice guide, are included in Appendix VI.

Table 9. Advantages and disadvantages of saltwater desalination

Advantages	Disadvantages
Supply reliability: Especially advantageous in the Loreto as they currently rely on only one source of water	**High cost**: Average per unit costs are nearly 5 times greater than traditional sources[24]
Less constraints on development: As more water would be available, more development would be possible	**High electricity requirements**: RO requires generally between 4 and 7 kWh per cubic meter[25]
High quality product water: When properly maintained, the quality of product water is generally high[24]	**Possible health concerns**: Contamination risk due to improper maintenance or operation[24]
Eliminate aquifer overdraft: inhibit contamination of the San Juan Londó freshwater aquifer by reducing groundwater overdraft	**Negative environmental impacts**: Marine life mortality from seawater intake, chemicals and other contaminants discharged with high concentration brine[25]
	Sense of unlimited supply: Could result in higher water demand[24]
	Socioeconomic impacts: Places high stress on the local economy

Though there are other desalinating technologies, we only considered reverse osmosis (RO) desalination, due to its increasing dominance worldwide, as well as its suitability for Loreto. For example, as of 2008, 63 of 67 plants in operation in BCS used RO technology[18]. The MCA includes two desalination alternatives, a large plant with high capacity and a small plant with low capacity.

Large Salt Water Desalination

In this analysis, a large desalination plant is a stand-alone project that has the capacity to meet the water supply needs for the entire region, under all population scenarios modeled in the MCA. While we use the term large desalination, it would be considered a medium sized plant compared to plants for major urban centers.

The large desalination plant in this analysis has a capacity of 15,000 m^3/day. Investment costs are calculated based on per unit investment costs of $1,176 for every cubic meter of capacity. Therefore, the total investment cost is estimated at $17,640,700[26]. Operation and maintenance costs are based on production, which is on average $0.66/$m^3$ for a large desalination plant. For each population scenario, we calculated the amount of water that would be necessary to meet the needs of the entire population and established the operation and maintenance costs accordingly. Appendix VI outlines details of these calculations. The energy requirements for desalination are very high (VH) in relation to other alternatives in the MCA. All quantitative and qualitative criteria values used for large desalination in the MCA are shown in Table 10.

Table 10. Large desalination criteria values

Criterion	Value
(1) Expected Yield	
Current Population	4.04
17,000 scenario	1.95
25,000 scenario	1.07
(2) Time to Implementation	ML
(3) Confidence in Yield	H
(4) Investment Costs (U.S. $)	17,640,700
(5) Operation and Maintenance Costs (U.S. $)	
Current Population	1,800,000
17,000 scenario	2,550,000
25,000 scenario	3,613,500
(6) Technical Sophistication	VH
(7) Environmental Impacts	VH
(8) Energy Requirement	VH
(9) Infrastructure Requirements	VH

Small Salt Water Desalination

We also consider small desalination plants that would be installed and operated by individual hotels or other tourist development projects. The expected yield for one small desalination plant in the MCA is based on the provision of 513 L/day for 500 people, corresponding to a large hotel or resort. We found this to be a reasonable size based on existing hotels and proposed projects in the Loreto region. The MCA evaluates implementation of a single small desalination plant for the current and the 17,000 population scenarios, and two small plants for the 25,000 population scenario.

Like with large desalination, investment costs are calculated based on unit investment costs[26]. The investment cost for a small plant is approximately $\$2,500/m^3$ of daily capacity. Therefore, the production of 513 L of water per day for 500 people results in an estimated total investment cost of \$653,200. Operation and maintenance costs are based on actual production, which is on average $\$2.05/m^3$ for a small desalination plant. This amounts to \$191,900 for one small plant to meet the needs of 500 people in our analysis. The energy requirements for a small desalination plant, like for the large desalination plant, are assigned a relative (compared to other alternatives) qualitative value of very high (VH). All quantitative and qualitative values for small desalination in the MCA analysis are shown in Table 11.

Table 11. Small desalination criteria values

Criterion	Value
(1) Expected Yield	
Current Population	0.07
17,000 scenario	0.03
25,000 scenario	0.04
(2) Time to Implementation	ST
(3) Confidence in Yield	H
(4) Investment Costs (U.S. $)*	
Current population, 17,000 scenario	652,200
25,000 scenario	1,304,500
(5) Operation and Maintenance Costs (U.S. $)	
Current population, 17,000 scenario	191,900
25,000 scenario	383,800
(6) Technical Sophistication	M
(7) Environmental Impacts	VH
(8) Energy Requirement	VH
(9) Infrastructure Requirements	M

*The analysis includes one plant for the current and the 17,000 scenarios, and two plants for the 25,000 population scenario.

Domestic Fixtures

Toilets, sinks and showers account for approximately 60% of domestic water use on average (Table 12), so installation of water-saving fixtures can significantly reduce household water consumption. Therefore, for future population scenarios, we incorporated an alternative for implementation of water-efficient fixtures in new construction projects. We focused on the water savings from a combination of three retrofitting devices—ultra low flush (ULF) toilets, low flow showerheads, and faucet aerators—that would provide Loreto with the greatest opportunity for domestic water use savings. Implementation of these fixtures can realistically achieve total savings of 26% (Table 12); using technologies that would meet the conservation objectives with a low end cost of $33 for one set of all three devices (Table 13). High-end costs for domestic fixtures can be found in Appendix VII.

Table 12. Potential household water savings with water-efficient domestic fixtures **

Domestic Water Use	Typical Household Water Use (%)*	Water Savings per Fixture (%)	Water Savings Based on Proportions (%)
Faucet	17	30	5.1
Shower	16	40	6.4
Toilet	26	54	14
Total	~60		~26

*SOURCE: [27] ** See Appendix VII for details on derivation of numerical values

Table 13. Low-end costs of domestic fixtures

Domestic Fixtures	Non-Efficient Cost $	Water-efficient Cost $	Difference ($)
Toilet (Brand: Kohler)	120.00 (3.5 gal*)	150.00 (1.5 gal)	32.00
Low Flow Shower Heads (Brand: American Standard)	15.40 (2.5 gpm**)	18.75 (1.5 gpm)	3.35
Faucet Aerator (Brand: AM)	3.00 (2.2 gpm)	0.89 (1.5 gpm)	-2.12
Total cost for set of all three fixtures($)			33.00

*gal=gallon, **gpm=gallons per minute

For the MCA, operational and maintenance costs were set at zero, as the average life for domestic fixtures is assumed to be over ten years without service or maintenance[28]. Additionally, we assume that the maintenance for water-saving fixtures does not differ from generic fixtures. The investment costs for each future population scenario are calculated using per capita costs, based on implementation of 2 sets of fixtures in each new four person household. Table 14 includes a complete list of quantitative and qualitative criteria values for domestic fixtures in the MCA analysis.

Table 14. Domestic fixtures criteria values

Criterion	Value
(1) Expected Yield*	
Current Population	n/a
17,000 scenario	0.09
25,000 scenario	0.12
(2) Time to Implementation	I
(3) Confidence in Yield	H
(4) Investment Costs (U.S. $)	
17,000 scenario	82,500
25,000 scenario	214,500
(5) Operation and Maintenance Costs (U.S. $)	0
(6) Technical Sophistication	L
(7) Environmental Impacts	VL
(8) Energy Requirement	VL
(9) Infrastructure Requirements	VL

*See Appendix VIII for specifications on expected yield values in combination with high conservation

Managed Aquifer Recharge

Managed aquifer recharge (MAR) is a technique for arid regions to replenish aquifers and allow subsequent recovery of water for urban, agricultural and environmental benefit[29]. Due to low precipitation and lack of perennial streams in Loreto, the most reliable water source for MAR is recycled wastewater. Currently, all treated wastewater in Loreto is sold to a local resort community for irrigation purposes. Therefore, MAR is only included as an alternative in future population scenarios of the MCA, when an increase in residents would generate additional treated wastewater. Because the SJL aquifer is believed to be primarily confined, direct injection wells are the most suitable option to recharge the aquifer. Wastewater treated in Loreto would be pumped 30 km to the SJL aquifer for injection. In this document, the otherwise general term MAR specifically refers to wastewater recharge via direct injection wells. More information on MAR by direct injection is found in Appendix VII.

In the MCA, we only included costs relating to the direct injection wells for investment and operation and maintenance costs criteria. Investment costs for one direct injection well, which includes drilling and engineering of the well and pump infrastructure, range between $500,000 and $1.5 million. We used the low-end cost based on relatively lower wages in México and the assumption that a low-cost method would more likely be implemented. A single recharge well has the capacity to accommodate all treated wastewater in both future population scenarios[30,31]. Operation and maintenance costs are found to be generally in the range of 4% of total capital investment costs[32,33], which translates into $20,000 in the MCA. Table 15 shows all MCA criteria values for MAR, and Appendix VII expands on the basis for these criteria values.

Table 15. Quantitative and qualitative values used for MAR

Criterion	Value
(1)Expected Yield	
Current Population	n/a
17,000 scenario	0.16
25,000 scenario	0.22
(2) Time to Implementation	ML
(3) Confidence in Yield	H
(4) Investment Cost ($)	500,000
(5) Operation and Maintenance Costs ($)	20,000
(6) Technical Sophistication	H
(7) Environmental Impacts	M
(8) Energy Requirements	L
(9) Infrastructure Requirements	H

While MAR may be technically viable in Loreto and has therefore been included in the MCA, more rigorous study is required to determine actual feasibility for the purpose (i.e. wastewater recycling) stipulated in this analysis. Of foremost concern, social acceptability would need to be considered. From the perspective of the Loreto community, alternative use, such as irrigation, may be the highest and best use of additional treated wastewater. Due to this underlying uncertainty, we accepted a number of otherwise disqualifying data limitations in the MCA, in order to evaluate whether the possibility of recharge by direct injection should be further explored, based on its performance compared to other alternatives in this analysis. More information on the uncertainties and data limitations of MAR by direct injection are in Appendix VII.

Model – Compromise Programming

In order to identify optimal solutions within this MCA framework, we used the Compromise Programming (CoPr) method to evaluate the alternatives. This MCA technique was primarily chosen because it is robust, easy to explain, and easily understood by decision makers[16]. CoPr analyzes a set of feasible alternatives in order to choose the best solution from the set by a measure of distance, whereby the best solutions are those that are closest to the ideal score[34,35]. To calculate the distance from the ideal, we used a commonly used metric‡ as described below:

$$L^i_{j,p} = \left[\sum_{i=1}^{I} w_i^p \left| \frac{f_{i,b} - f_{i,j}}{f_{i,b} - f_{i,w}} \right|^p \right]^{1/p}$$

where $L^i_{j,p}$ is the distance metric to be minimized; $f_{i,j}$ is the value of an alternative *j*, for a given criterion *i*; $f_{i,b}$ and $f_{i,w}$ are the best and worst values for a criterion; w_i is the weight reflecting the relative importance of criterion *i*; and *p* is a parameter reflecting the importance of the maximal deviation from the ideal. The ratio in the formula normalizes all objective functions within the dimensionless range of 0 to 1, as not all units are commensurable.

Evaluation of Alternatives/Evaluation Matrix

The values for all alternatives were entered into an evaluation matrix that includes both quantitative and qualitative values as shown in Table 16 for the current population. To incorporate them into the distance-based calculations, qualitative inputs were substituted by numerical values. As shown in Table 9, the qualitative ranges (low to high and very low to very high) were assigned numerical values ranging from one to five. In addition, the expected yield was capped for a maximum achievement of 100% of overdraft coverage. Evaluation matrices for future population scenarios, which include criteria values for domestic fixtures and MAR, are included in Appendix VIII.

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‡This metric is also known as the Lp-metric[35].

For the following tables, alternatives are abbreviated as listed below:

Alternative	Abbreviation of Alternative
Low Conservation	LC
High Conservation	HC
Infrastructure Upgrades	IU
Small Desalination	SD
Large Desalination	LD
Domestic Fixtures	DF
Managed Aquifer Recharge	AR

Table 16. Evaluation matrix of qualitative and quantitative values for the current population

	Alternatives				
Criteria	**IU**	**HC**	**LC**	**SD**	**LD**
(1)Expected Yield	0.90	0.36	0.08	0.07	4.04
(2) Time to Implementation	ML	LT	M	ST	ML
(3) Confidence in Yield	H	M	M	H	H
(4) Investment Costs ($)	364,700	247,700	29,700	652,200	17,640,600
(5) Operation and Maintenance Costs ($)	0	0	0	191,900	1,800,000
(6) Technical Sophistication	M	VL	VL	M	VH
(7) Environmental Impacts	M	VL	VL	VH	VH
(8) Energy Requirements	VL	VL	VL	VH	VH
(9) Infrastructure Requirements	L	VL	VL	M	VH

Immediate (I), Short Term (ST), Medium (M), Medium-Long (ML), Long-term (LT), Very Low (VL), Low (L), High (H), Very High (VH)

Table 17. Evaluation matrix of numerical translations for the current population

	Alternatives				
Criteria	**IU**	**HC**	**LC**	**SD**	**LD**
(1)Expected Yield	0.90	0.36	0.08	0.07	1
(2) Time to Implementation	4	5	3	2	4
(3) Confidence in Yield	3	2	2	3	3
(4) Investment Costs	364,700	247,700	29,700	652,200	17,640,600
(5) Operation and Maintenance Costs	0	0	0	191,900	1,800,000
(6) Technical Sophistication	3	1	1	3	5
(7) Environmental Impacts	3	1	1	5	5
(8) Energy Requirements	1	1	1	5	5
(9) Infrastructure Requirements	2	1	1	3	5

Since several individual alternatives can be implemented simultaneously or as constituents of a comprehensive strategy, we developed programs by combining multiple alternatives in a systematic fashion to generate all possible combinations[§]. In general, the criteria values were aggregated across the alternatives included in the program. Exceptions are time to implementation, and investment costs and expected yield in certain programs that include domestic fixtures. Table 18 shows programs for the current population scenario. Programs for future population scenarios are listed in Appendix VIII.

Table 18. Programs for the current population

	Alternatives				
Program	**IU**	**HC**	**LC**	**SD**	**LD**
1	X				
2		X			
3			X		
4	X	X			
5	X		X		
6				X	
7					X

Programs are evaluated based on their distance from the ideal value out of all programs. In our analysis, the ideal is the best value for a particular criterion across all programs, which may either constitute a maximum or minimum. The basis for the ideal and the best and worst values the current population are listed in Table 19. Values for future population scenarios are listed in Appendix VIII.

[§] Mutually exclusive alternatives low and high conservation and small and large desalination were not combined in the programs.

Table 19. Programs versus criteria for the current population

	Criteria								
Programs	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**(8)**	**(9)**
1	0.90	4	3	364,700	0	3	3	1	2
2	0.36	5	2	247,700	0	1	1	1	1
3	0.08	3	2	29,700	0	1	1	1	1
4	1.26	5	5	612,500	0	4	4	2	3
5	0.98	4	5	394,500	0	4	4	2	3
6	0.07	2	3	652,200	191,900	3	5	5	3
7	1.00	4	3	17,640,600	3,613,500	5	5	5	5
Basis for Ideal	Max	Min	Max	Min	Min	Min	Min	Min	Min
Best	1.26	2	5	29,700	0	1	1	1	1
Worst	0.07	5	2	17,640,660	3,613,500	5	5	5	5

Weights

The MCA weight assignments allow decision makers to designate the relative importance of the criteria in the model[16]. In this analysis, each criterion was assigned a weight ranging from 0-1 under each weighting scheme. For all but the equal weighting scheme, the sum of all nine criteria weights within a scheme equals one. By the process of assigning criteria weights that sum up to one, decision makers are forced to make trade-offs among the importance of each specific criteria.

The preference structure reflected in weights can significantly influence the final ranking and evaluation of the results in a MCA; therefore, we generated various sets of weights to reflect a range of preferences/objectives[36]. This process of iteratively trying out a variety of weighting schemes provides insights into the possible tradeoffs between each solution[16].

We used eleven total weighting schemes as shown in Tables 12 to 14 below. Weighting schemes 1-3 provide a range of different perspectives and consist of: equal weighting amongst all alternatives; highest relative importance of environmental impacts, reflecting an environmental perspective; and highest relative importance of investment costs, reflecting an investor's perspective (Table 20). Weighting schemes 4-8 prioritize various criteria based on our informed assessment of the different perspectives in Loreto. These include weighting schemes that prioritize investment costs, operation and maintenance costs, time to implementation, environmental impact, and expected yield (Table 21). Weighting schemes 9-11 were based on priority rankings assigned by local contacts, including a former water manager (Table 22).

Table 20. Weighting schemes 1-3: (1) equal weighting, (2) environmental perspective, (3) investor's perspective

Criteria	Weighting Scheme 1	Weighting Scheme 2	Weighting Scheme 3
(1) Expected Yield	1	0.15	0.12
(2) Time to Implementation	1	0.04	0.15
(3) Confidence in Yield	1	0.04	0.1
(4) Investment Costs	1	0.1	0.2
(5) Operation and Maintenance Costs	1	0.04	0.09
(6) Technical Sophistication	1	0.04	0.15
(7) Environmental Impacts	1	0.4	0.05
(8) Energy Requirements	1	0.15	0.05
(9) Infrastructure Requirements	1	0.04	0.09

Table 21. Weighting schemes 4-8. Weighting scheme prioritization: (4) Time to implementation and confidence in yield; (5) expected yield, investment costs, and operation and maintenance cost; (6) environmental impacts and operation and maintenance costs; (7) investment costs, operation and maintenance costs, and expected yield; (8) investment costs, expected yield, operation and maintenance costs, and environmental impacts

Criteria	Weighting Scheme 4	Weighting Scheme 5	Weighting Scheme 6	Weighting Scheme 7	Weighting Scheme 8
(1) Expected Yield	0.2	0.2	0.14	0.19	0.18
(2) Time to Implementation	0.4	0.06	0.12	0.1	0.09
(3) Confidence in Yield	0.25	0.1	0.05	0.06	0.06
(4) Investment Costs	0.025	0.2	0.16	0.2	0.19
(5) Operation and Maintenance Costs	0.025	0.2	0.18	0.19	0.18
(6) Technical Sophistication	0.025	0.06	0.05	0.06	0.04
(7) Environmental Impacts	0.025	0.06	0.2	0.08	0.18
(8) Energy Requirements	0.025	0.06	0.05	0.06	0.05
(9) Infrastructure Requirements	0.025	0.06	0.05	0.06	0.03

Table 22. Ranking and weighting schemes 9-11, based on priority rankings assigned by Loreto contacts: (9) Local A, (10) Local B, and (11) Local C

Criteria	Weighting Scheme 9	Ranking for Scheme 9	Weighting Scheme 10	Ranking for Scheme 10	Weighting Scheme 11	Ranking for Scheme 11
(1) Expected Yield	0.133	4	0.190	1	0.044	8
(2) Time to Implementation	0.178	2	0.048	7	0.067	7
(3) Confidence in Yield	0.111	5	0.024	8	0.022	9
(4) Investment Costs	0.2	1	0.143	3	0.133	4
(5) Operation and Maintenance Costs	0.067	7	0.143	3	0.156	3
(6) Technical Sophistication	0.156	3	0.119	4	0.2	1
(7) Environmental Impacts	0.022	9	0.167	2	0.089	6
(8) Energy Requirements	0.044	8	0.095	5	0.178	2
(9) Infrastructure Requirements	0.089	6	0.071	6	0.111	5

Running the Model

After conducting steps one through four in the MCA process, we ran the model for all three population scenarios. During a first round of runs, we included all possible programs without consideration of the existing aquifer overdraft. In the second round of model runs we only evaluated programs that meet the aquifer overdraft based on their cumulative expected yield.

Sensitivity Analysis

We conducted a two-part sensitivity analysis, in order to evaluate the stability of optimal solutions identified by the model runs. The first part of the sensitivity analysis consisted of running the model under all established weighting schemes. Our use of multiple weighting schemes shows how sensitive the various water management programs in the model are to decision maker preferences, where certain criteria are given a greater relative importance. This is important in order to determine whether the manipulation of weights drastically changes outcomes of the MCA and can thereby be used to influence the results.

The second part of the sensitivity analysis consisted of increasing the parameter p of the CoPr equation from 1 to 2. This parameter reflects the importance of the maximal deviation from the ideal value, so that by increasing the value of the parameter, the deviation is penalized. Additionally, it magnifies the criteria weights, and thereby the relative importance of a given criterion[36].

Results and Analysis

Overall results across all population scenarios and weighting schemes show prominent optimal solutions. Conservation rankied the highest, followed by domestic fixtures and infrastructure upgrades, either individually or in combined programs. Large desalination ranks high in the 25,000 population scenario, where no program can otherwise meet the freshwater needs of the population. However, it is not a preferred solution in any other scenario. The sensitivity analysis shows further, that these results are relatively robust. Generally, different weights can dramatically change the final ranking and evaluation of the results. However, across the range of eleven weighting schemes used in our analysis, specific programs consistently emerge on top.

Part 1: Evaluation of all Alternatives in the First Run of the CoPr Model

We first evaluated all possible programs without consideration of the aquifer deficit, meaning that every program was included whether or not it fully covers the aquifer deficit under any particular population scenario. This step allowed us to key in on optimal programs that should be given priority in Loreto, under all circumstances. These programs would take precedence whether they are implemented alone or later supplemented by other alternatives.

Table 23 below shows the top three rankings for each population scenario using weighting schemes 1-3 outlined in Table 11 in the previous section. These schemes include equal weighting, an environmental perspective, and a scheme reflective of an investor's perspective. Results for all eleven weighting schemes for each population scenario are included in Appendix IX.

For the current population, conservation ranks highest, with low conservation more prominent than high conservation. Infrastructure upgrades also emerge among the top three positions across these weighting schemes.

For both future populations, domestic fixtures rank first in all three weighting schemes. Conservation and infrastructure upgrades also emerge as top solutions for the 17,000 population, whereas conservation is the only additional preferred solution for the 25,000 population scenario.

Table 23: Top three results for all population scenarios for three weighting schemes

Rank	Weighting Scheme 1	Weighting Scheme 2	Weighting Scheme 3
Current Population			
1	Low Conservation	High Conservation	Low Conservation
2	High Conservation	Low Conservation	Infrastructure Upgrades
3	Infrastructure Upgrades	Infrastructure Upgrades	Infrastructure Upgrades + Low Conservation
17,000 Population Scenario			
1	Domestic Fixtures	Domestic Fixtures	Domestic Fixtures
2	Infrastructure Upgrades	High Conservation	Low Conservation
3	Low Conservation	Infrastructure Upgrades	Infrastructure Upgrades
25,000 Population Scenario			
1	Domestic Fixtures	Domestic Fixtures	Domestic Fixtures
2	Low Conservation	High Conservation	Low Conservation
3	Low Conservation + Domestic Fixtures	Low Conservation	Low Conservation + Domestic Fixtures

While the results presented here include only three of the eleven total weighting schemes, they effectively represent the results across all schemes. In order to highlight trends in the results, we assigned cumulative points for the top three solutions within each weighting scheme. Figure 3 shows the optimal alternatives based on their cumulative points among all eleven weighting schemes, whether they occur individually or in combined programs.

For all of the following figures, alternatives are abbreviated as listed below:

Alternative	Abbreviation of Alternative
Low Conservation	LC
High Conservation	HC
Infrastructure Upgrades	IU
Small Desalination	SD
Large Desalination	LD
Domestic Fixtures	DF
Managed Aquifer Recharge	AR

For the current population scenario, the three examples in Table 15 are dominated by conservation and infrastructure upgrades, alone or in combined programs. Across all weighting schemes, aggregated results show that, whether individually or in combination, conservation ranks the highest, followed by infrastructure upgrades (Figure 3). The top programs for the current population are low conservation, followed by infrastructure upgrades, and a combination of low conservation with infrastructure upgrades (Figure 4).

Figure 3. Optimal alternatives across all population scenarios and all eleven weighting schemes, based on cumulative points

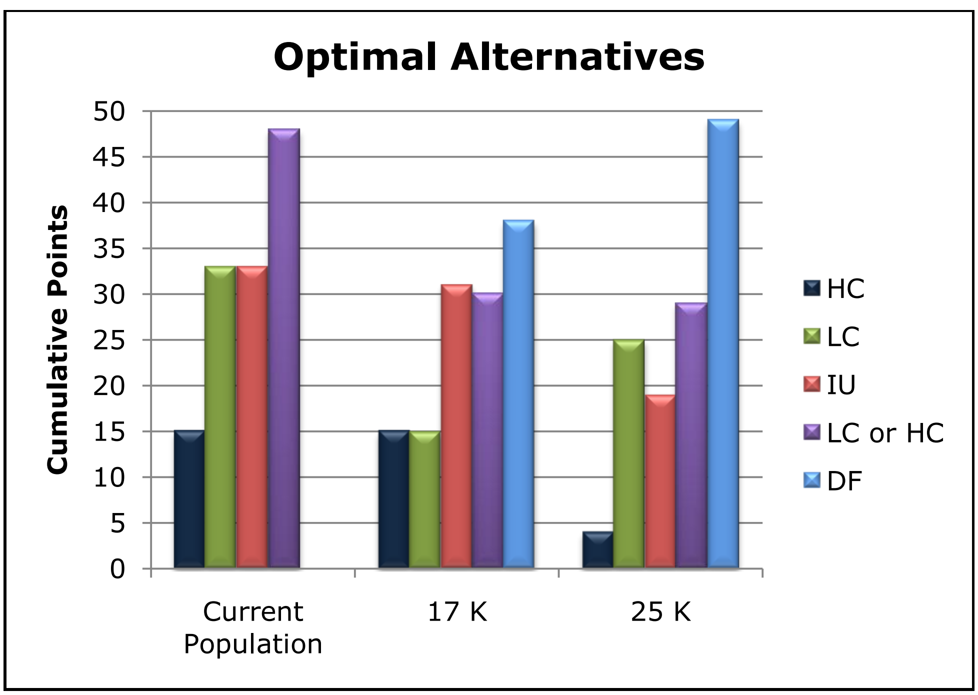
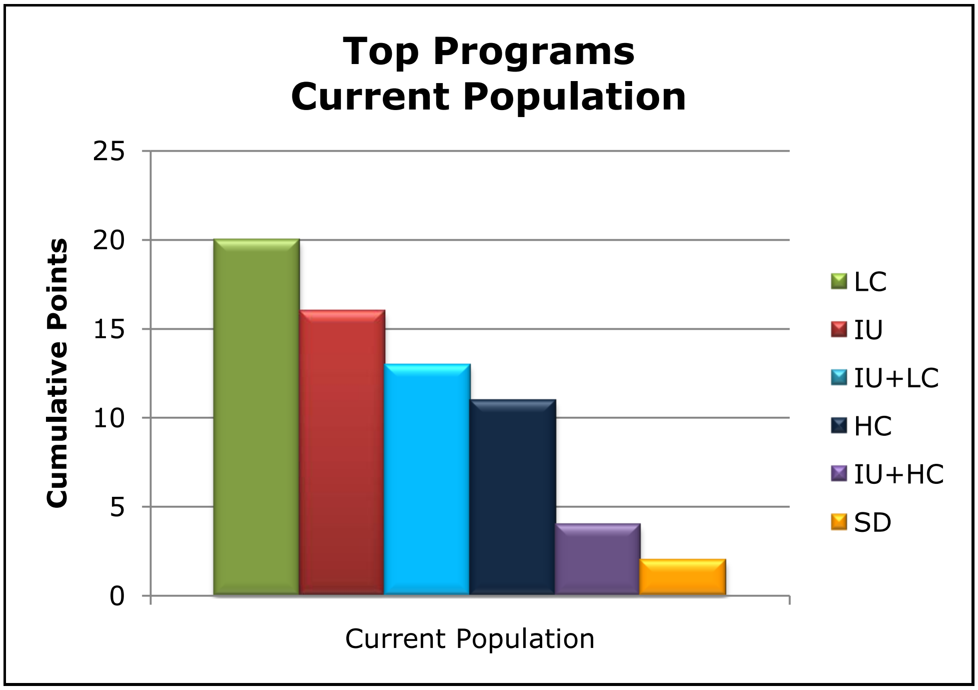


Figure 4. Top programs for the current population across all weighting schemes, based on cumulative points



For both future population scenarios, the optimal alternative is domestic fixtures, which is not included in the current population scenario. For the 17,000 population scenario, domestic fixtures receive the highest cumulative points followed by infrastructure upgrades and the conservation alternatives (Figure 5). For the 25,000 population scenario, high conservation is the second most important program, followed by domestic fixtures in combination with either infrastructure upgrades or low conservation (Figure 6).

Figure 5. Top programs across all weighting schemes for the 17,000 population

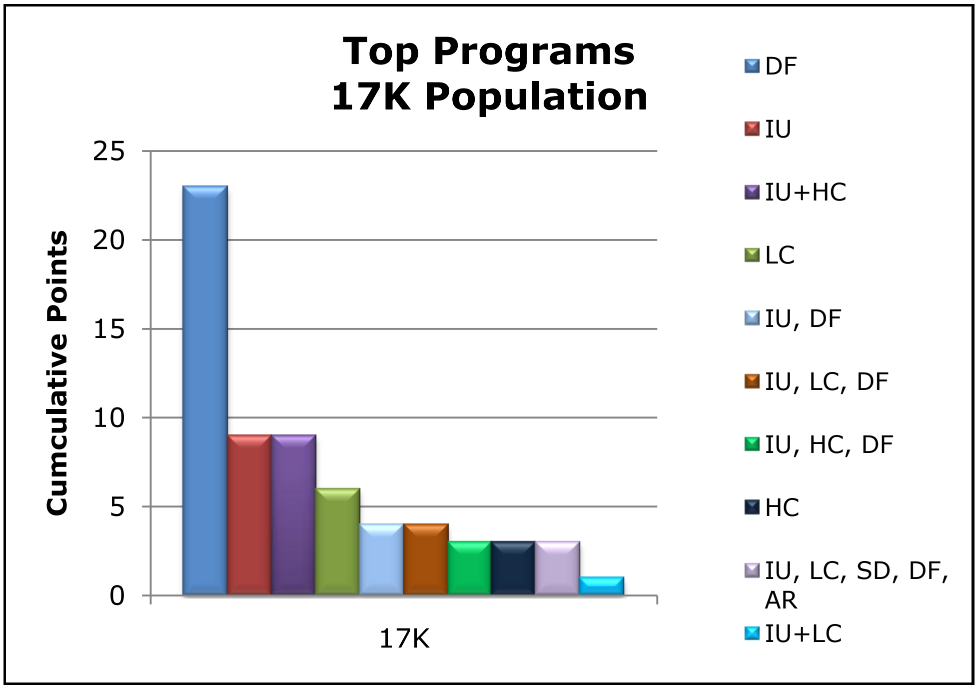
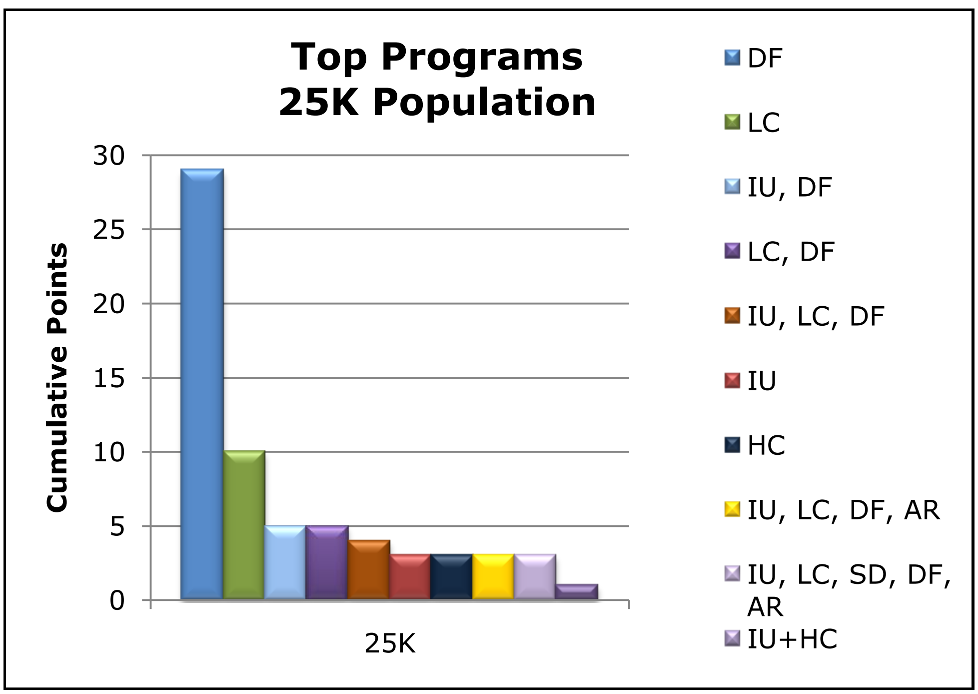


Figure 6. Top programs across all weighting schemes for the 25,000 popluation scenario



Like in the current population, the results across all weighting schemes for future populations reinforce the results of the three representative schemes in Table 12. Overall, conservation and infrastructure upgrades, as well as domestic fixtures emerge as the optimal results. Their consistent appearance indicates that demand-side alternatives—by themselves or combined—should be given the highest priority in Loreto, regardless of population level.

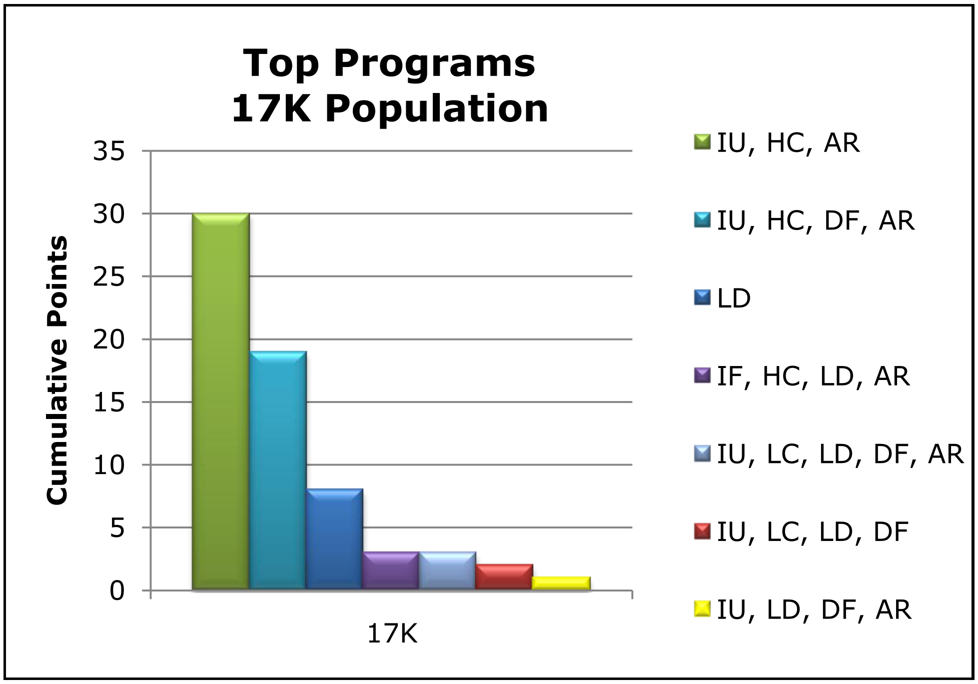
Part 2: Evaluation of Programs with Consideration of the Aquifer Overdraft

Part two of our analysis exclusively considers alternatives and combined programs that cover the aquifer deficit as calculated for each population scenario.

For the current population, only two programs would cover the aquifer overdraft: infrastructure upgrades in combination with high conservation, and a large desalination plant. The results show that the combination of infrastructure upgrades and high conservation clearly outperforms large desalination and ranks first across all weighting schemes. In addition, infrastructure upgrades and high conservation would provide an expected yield of 125% of the aquifer overdraft. Therefore, large desalination is neither necessary nor desirable at the current population level.

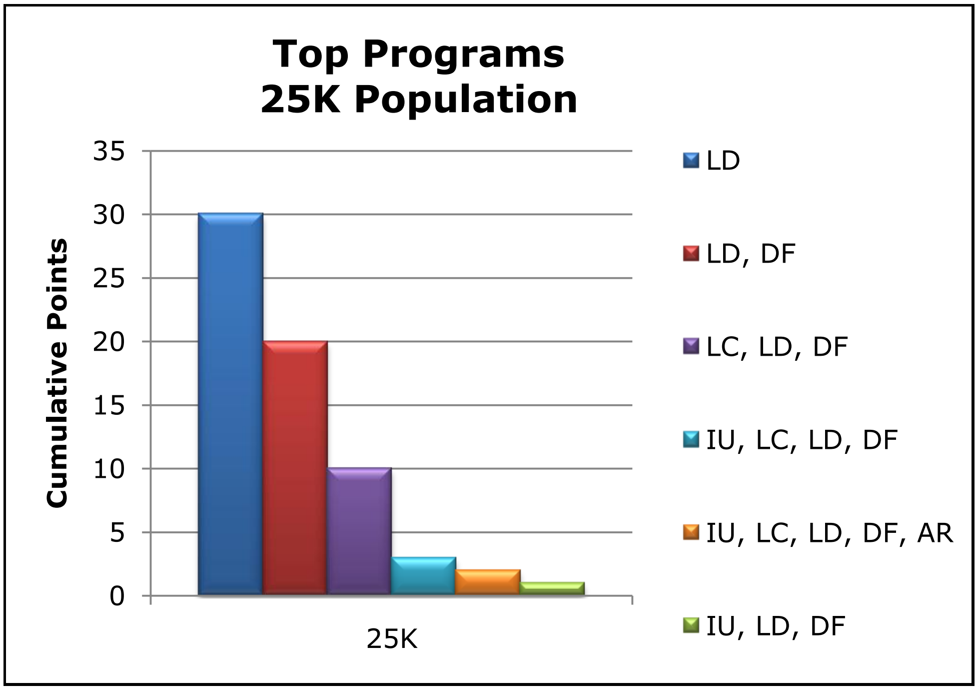
The 17,000 population scenario results are shown in Figure 7. The top two spots, which far exceed the other alternatives, include combinations of infrastructure upgrades, high conservation, MAR and domestic fixtures. Large desalination is a distant third best option, indicating that it is also a suboptimal alternative for a population of 17,000.

Figure 7. Top results across all weighting schemes for programs that cover the aquifer deficit for the 17,000 population scenario



In the 25,000 population scenario (Figure 8), large desalination is necessary to cover the aquifer deficit; consequently, it is included in every program considered for this scenario. The appearance of large desalination in the top rank indicates that it would be the optimal means of overcoming the aquifer overdraft, if the population of Loreto more than doubled, *and* if no interim improvements in efficiency or conservation were made.

Figure 8. Top results across all weighting schemes for programs that cover the aquifer deficit for the 25,000 population scenario



Individual results for all eleven weighting schemes are shown in Appendix X.

Part 3: Sensitivity Analysis

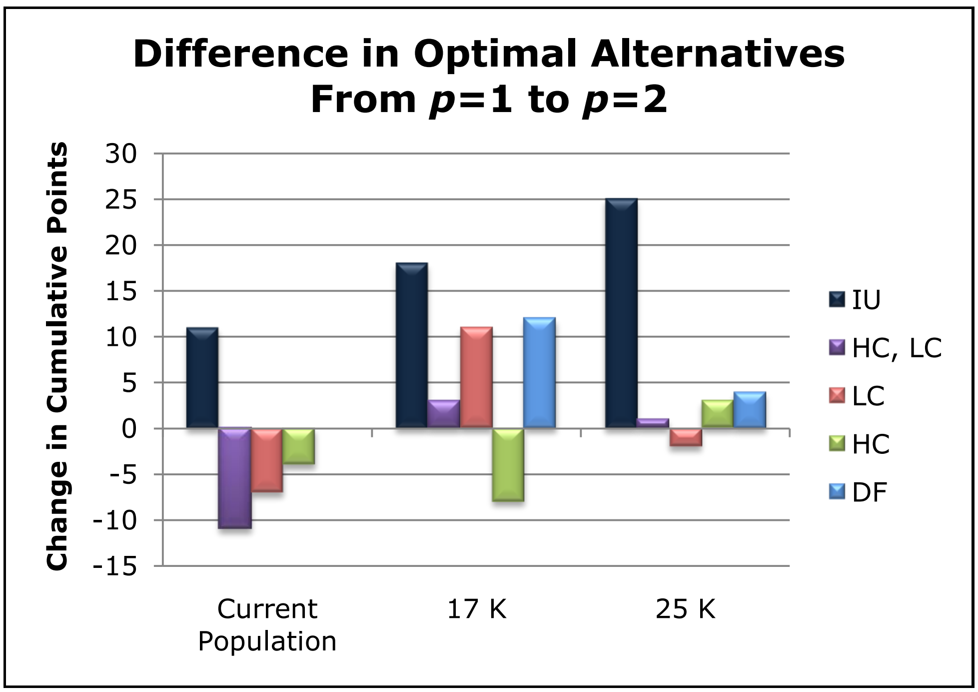
To assess the stability of modeled outcomes, we looked at changes in results across the eleven different weighting schemes and additionally when increasing the value of parameter p from 1 to 2.

The above results show that weighting does not significantly change outcomes, indicating a low sensitivity to weighting schemes. Among all eleven weighting schemes there is high consistency within the top three ranks of all results. While there are slight fluctuations within the first position, the general consistency of domestic fixtures, conservation, and infrastructure upgrades in the top three infers that these should always be among the top priorities of decision makers. The first implementation priority would then only be established by specific decision maker preferences, under given conditions in Loreto.

By increasing the parameter *p*, we tested sensitivity based on the maximal deviation from the ideal value. Alternatives that have the least deviation overall are considered robust alternatives. For example, Appendix XI includes a table of the normalized deviations of all programs considered in the current population scenario. As the parameter *p* increases in value, these robust alternatives tend to remain at the same rank or increase in rank.

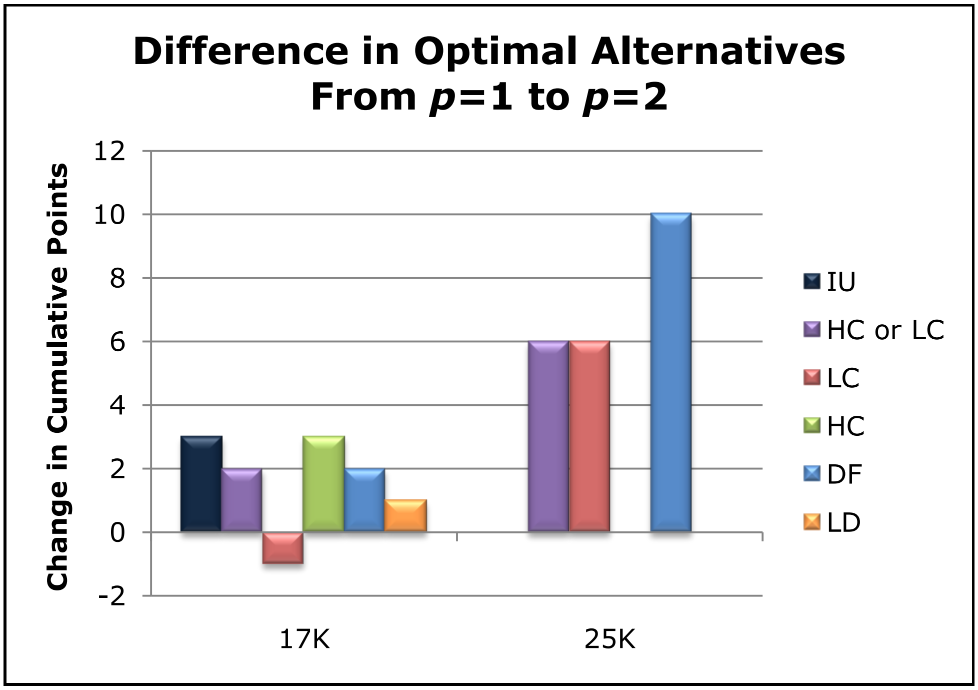
The most robust alternative is infrastructure upgrades. This alternative significantly increases in frequency among the top three ranks of all population scenarios when *p* is changed to 2 in Part 1 of this analysis (Figure 9). Less robust options, such as the conservation alternatives, decrease in frequency among the top three ranks from *p*=1 to *p*=2.

Figure 9. Changes in Part 1 results from *p*=1 to *p*=2, for all population scenarios



Sensitivity analysis of Part 2 results, which include only programs that cover the aquifer overdraft, shows the greatest positive changes among the conservation alternatives, indicating their stability under these conditions. For the 25,000 population scenario, the conservation alternatives also rank among the top three more often with *p*=2 than with *p*=1 (Figure 10).

Figure 10. Changes in Part 2 results from *p*=1 to *p*=2, for future population scenarios



The results presented here provide a guideline on how water resources should be managed and considered in Loreto. However, the flexibility of the MCA as a dynamic decision-making framework is equally important to the project goal of developing strategies for sustainable water supplies. This flexibility allows the analysis to be modified by decision makers based on local priorities and as circumstances change over time in Loreto. Yet, while this framework can support the decision-making process, existing political and institutional constraints challenge water resources management in Loreto and may limit its effectiveness.

Water Politics and Management

In order for the framework to be successfully employed, political and institutional constraints need to be overcome. In this section we consider the factors influencing the current situation in Loreto by looking at water policy and practices in México. Our intent is to assess opportunities to improve water management within existing policies and laws, in order to propose means of implementing more effective management in Loreto.

History

Based on Mexican Constitutional law, the Mexican government has proprietary rights over all water resources within its territorial boundaries. Therefore, water can only be used or allocated by concessions granted by the federal government—either to individuals, to private companies, or to states or municipalities for management and delivery. The Mexican government delegates water administration to the National Water Commission, *Comisión Nacional del Agua* (CONAGUA), which is tasked with managing and preserving national water resources through cooperation with states and municipalities.

In the 1980's, in an effort to decentralize water services, the Mexican government assigned various responsibilities—including potable water delivery and administration, wastewater handling, and sewage treatment—to municipalities[37]. Yet, municipalities assumed these water management responsibilities without the expertise of prior experience, or the training necessary to acquire such expertise. Further, decentralization doubled municipalities' administrative responsibilities, budgetary requirements, and functions, but the federal government failed to fully provide the necessary financial resources. This deficiency in funding led to both deterioration of water delivery infrastructure and ineffective management[38]. Complicating the situation, the legacy of indifferent water management by the federal government is demonstrated by the low frequency of water tariff bill payments in most areas of México[39]. For decades, the government inconsistently registered water users, which led to poor billing capability. While reform measures in conjunction with decentralization have managed to improve water user registration throughout México, the financial situation remains tenuous in most states and municipalities, due to legal complications. Further, access to water is guaranteed to citizens by the Mexican constitution (Article 121, see Appendix XII), which legally prohibits suspension of potable water service for any reason, including non-payment by water users. This right to potable water is well-intentioned, but inhibits means of payment enforcement that might otherwise help to overcome the financial issues that currently constrain municipal water management.

As a result of these challenges, public water management in México overall remains a significant social and economic challenge. Although certain localities successfully manage water distribution and administration, the national urban supply system has: an efficiency of less than 30%, estimated losses of 30-50% by transport through leaky infrastructure, low billing frequency by municipal utilities, and a collection rate of only about 60% of the invoices actually billed[40].

As these problems became clear, a general concern arose in the Mexican government that public entities lack the technical, administrative, and financial capability to manage urban water supplies[40]. Therefore, in an effort to improve freshwater management in 1991, the Mexican government revised the *Ley de Aguas Nacionales* (National Water Law) to allow for private water administration[37]. Consequently, current water management regimes in México include a mix of private, public, and a combination of both. Public management—such as that in Loreto—falls under state or municipal authority; private enterprises are governed by outside investors; and Mexico City, for example, combines elements of both public and private management.

México Water Management Regimes

There are examples of successful and inadequate water management under both public and private regimes; however, successful efforts share common attributes. The biggest successes: increase the number of citizens connected to potable water services; improve sanitation and wastewater treatment; increase efficiency; successfully mediate the water needs of competing users; and improve administration—specifically billing, collections, and customer service. An example of successful privatization is in Cancun, where the booming tourist economy allowed a shift of the primary financial burden from citizens to hotels[41]. The public utilities in Monterrey and Tijuana have proven very effective at water management. In addition, the successful publicly-managed effort in the state of Guanajuato effectively incorporates community involvement[42,43]. Given the current situation in Loreto, Guanajuato provides the most instructive example of the possibility to locally improve water management.

Water Management in Loreto

Water distribution in Loreto is managed by *Organismo Operador Municipal del Sistema de Agua Potable y Alcantarillado de Loreto*, (Municipal Operating Agency of the Loreto Potable Water and Sewer System, OOMSAPAL), a public utility. OOMSAPAL is headed by a water manager appointed by the municipal president at the beginning of his/her 3-year term, yet the appointment does not depend on prior experience in a water management capacity[10]. At the same time, Loreto is plagued by the same inefficient water distribution system and administrative difficulties that characterize México at large. For example: Loreto loses approximately 35% of pumped water in the distribution system between the aquifer and water users, only 32% of customers are billed, and only 60% of billed customers actually pay, which amounts to payments by less than 20% of total urban and domestic water users[44].The combined lack of experience, lack of continuity due to frequent management turnover, and legal and cultural status quo challenge water management in Loreto. However, the political provisions included in the National Water Law revision may offer an opportunity to facilitate more effective management.

Outlook for Loreto

While a great deal of emphasis is on water privatization in México, this is not currently an option for Loreto because a minimum population of 50,000 is necessary for the profit potential to attract investors[37]. However, the revised National Water Law also included a key provision for public water management: the possibility of water user participation through autonomous councils made up of community members. The non-profit councils are divided into four levels of decreasing geographic scope: basin-level councils, subbasin commissions, micro-basin committees, and groundwater technical committees for individual aquifers. Of the four, the aquifer-level groundwater technical committees (*Comités Técnicos de Aguas Subterráneas*, COTAS**), form the primary basis for community-level involvement in urban-domestic water management decision-making[45]. A COTAS receives financial and functional support from the federal or state government, but is staffed and driven by community members[43].

To date, COTAS have not been widely implemented in México. The most successful effort has been in Guanajuato, one of the best examples of public water management in general. A case study of Guanajuato's management is included in Appendix XIII. Given the deep interest of Loreto citizens in civic matters, shown most notably by the highest rate of political participation in BCS[46], we see the community-based COTAS provision as the most promising opportunity to improve water management decision-making in Loreto.

** Note that the COTAS acronym can be used for either singular or plural reference in this text

Discussion

Loreto and COTAS

We believe that a community-based COTAS would have significant potential to overcome the water management discontinuity in Loreto. This potential is evident in local citizens' past and present engagement in civic affairs and their support for long-term sustainable practices that protect their environment and economic opportunities. For example, Loreto has the highest percentage of political participation in the state of BCS, averaging 76% in the last four elections, compared to an average of 56% across other municipalities in the state[46]. In addition, community members have actively advocated for more sustainable development. To counter FONATUR's push for rapid growth, a citizens' organization proposed a more sustainable master plan called Loreto 2025. Loreto 2025 earned substantial community support for its proposal to cap growth and restrict development to certain areas. Our client, Eco-Alianza, also has significant community support—including active, influential board members, and alliances with local businesses and politicians—for its initiatives to promote more sustainable governance and balance economic development with social and environmental well-being. Finally, the community established the LBNP to responsibly govern local marine resources. To further that effort, a range of community stakeholders participated in a recent agreement to implement greater protection and more sustainable use of the biodiverse marine park.

Given this community interest and willingness to champion a more sustainable path, a COTAS offers Loretanos an opportunity to also influence water management decision-making. A COTAS in Loreto, financed by the federal or state government, would be staffed and run by community members. Equally important, it would not be subject to the staff turnover of political term limits, and could therefore provide continuity to the vision, process and execution of water management. The ability to meaningfully influence management of water resources by a formal process could also encourage stewardship over the financial challenges as well as foster a sense of responsibility for outcomes of the decision-making process.

Water Demand Management

Results from the MCA showed that demand-side management measures should take precedence over projects to secure additional freshwater supplies in Loreto. Specifically, infrastructure upgrades and conservation programs should be given priority at all population levels and water-efficient domestic fixtures should also be installed in all future development projects.

These measures can free up substantial amounts of water to satisfy current and higher future water demands. For example, reducing per capita water use of the current population to 400 L/day through the high conservation program and increasing distributional efficiency to 100% through infrastructure upgrades would free up enough water to make up for the aquifer deficit and meet the needs of an additional 3,200 people. Further details of the potential of water demand reductions in current and future population scenarios are included in Appendix V.

Despite the significant gains to be had from conservation and efficiency improvements, our analysis indicates that desalination is inevitable if Loreto's population continues to increase beyond a certain point, and if circumstances remain unchanged in the interim (e.g. no new technologies or imported water). If desalination becomes necessary, a number of considerations should be taken into account in planning and implementation.

Desalination and Loreto

Compared to the other alternatives, desalination introduces the highest potential for environmental impacts. Of particular concern is the LBNP, which underpins the local tourist and fishing economy. Specifically, intake systems threaten marine life with entrainment and impingement and brine discharged into the sea can have far-reaching effects on the surrounding marine ecosystem. More details on impacts from desalination and mitigation strategies are found in Appendix VI. While the impacts vary widely depending on the care taken in site and technology selection, the fact remains that no similar risks are associated with other alternatives in this analysis. Additionally, the desalination process requires a great deal of energy compared to other alternatives. This energy would not only tax the capacity of the isolated BCS energy grid, but its generation has upstream environmental impacts. In order to minimize the various impacts, desalination should only be undertaken when necessary to satisfy the population's freshwater needs, and after careful environmental review.

However, desalination is not currently subject to an independent assessment process in BCS, including the municipality of Loreto. Small desalination projects associated with new hotels in BCS are approved within the development design, as a mitigating strategy to meet additional water supply needs associated with the project. Consequently, the direct or indirect (e.g. energy use) impacts on the environment are neither assessed nor considered in small desalination project approval. In addition, while it is current practice in the U.S. and elsewhere, no existing policy requires an environmental review of a stand-alone desalination plant in the Loreto municipality. This absence of oversight increases the likelihood of negative impacts associated with future desalination plant proposals.

The lack of a policy also decreases the possibility that renewable energies will be considered to meet desalination plant energy requirements. The use of renewable energy sources would: avoid further demands on BCS electricity supplies, eliminate the upstream environmental impacts of electricity generation, and lower operation and maintenance costs of desalination plants. To date, five small-scale renewable energy desalination facilities have been built and operated successfully in BCS[18]. All have utilized solar power, from solar stills to photovoltaic arrays. Financial challenges due to their isolation in small, remote or rural communities ultimately resulted in the closure of all of them except the largest capacity facility, the photovoltaic plant which produced up to 19 m^3 of freshwater per day from seawater as of 2008[18]. Minimally, given the previous deployment and operation of solar powered desalination in BCS, this technology should be considered for small plants proposed in Loreto.

Data Limitations and Management Opportunities

The results of our MCA are based on a wide range of data and simplifying assumptions (Appendix II), as well as the current circumstances in Loreto. The underlying data and assumptions required us to apply informed judgments, including assessment of competing information, dealing with incomplete information, and accounting for uncertainty. As a result, actual opportunities for water resources management in Loreto could indeed be different and potentially greater than identified through the analysis.

Due to the use of conservative expected per capita gains, conservation efforts could yield far greater savings than specified in our analysis. Based on the suggested per capita need for Loretanos, we used 375 L/day[11] as the minimum goal for water conservation. Reducing per capita water use from the baseline amount of 513 L/day would be equivalent to 27%, which served as the basis for our calculations of potential savings from implementation of a high conservation program. This alternative assumes an achievement of 80% of the conservation goal, translating into 22% actual savings from baseline values and an actual new per capita use of 400 L/day. However, considering that the BCS average per capita water use is 300 L/day[1], there is potential for 42% water savings, nearly double the low estimate included in our MCA model. Scenarios of potential water savings through conservation programs are included in Appendix V.

Reductions through conservation free up water to meet the needs of larger populations without the need for new supply sources. For example, the MCA analysis showed that a large desalination plant is necessary to meet the needs of a population of 25,000 based on the current use conditions, and achievement of only the conservative water savings estimates in the MCA model. However, given the per capita use of 513 L/day and system inefficiencies, it is possible to achieve use savings of 42% in addition to recovery of 35% losses in the water distribution system, further delaying the necessity of desalination. Such water demand reductions—achievable by education programs geared towards changing use patterns, installation of water-saving domestic fixtures, and upgrades of distribution system infrastructure—can dramatically reduce the total amount of water required for any population level. This reduction then delays or minimizes the necessity for water supply augmentation measures, such as desalination.

At the same time, many of our calculations were based on available estimates of the current aquifer overdraft, which is tied to uncertainties. A number of published and unpublished studies have attempted to estimate the SJL water balance in order to determine current or future overdraft[2,9]. Difficulties in establishing accurate estimates of natural recharge, in addition to uncertainties in actual extraction rates, among other factors, have led to different conclusions across the studies. While a hydrogeological study has been conducted in recent years, further research is warranted to obtain more accurate information on the current overdraft and the potential sustainable yield of the SJL aquifer. For this analysis, we used the most recent scientific study[9], which falls within the middle range of all overdraft estimates. The study's conclusions are also supported by data from other sources that were available to us, such as actual pumping rates in Loreto. Nonetheless, these overdraft values may be either an over or under estimation.

The data for recharge by direct injection is also very limited. However, this MAR scheme did not perform well in the MCA, compared to the other alternatives considered. Therefore, while more information could be obtained, the additional data would most likely negatively affect MCA performance of this alternative. For instance, investment costs, operations and maintenance costs, and energy use would probably all increase, and therefore deviate farther from the ideal for those criteria. This indicates that direct injection recharge is a generally suboptimal solution to augment aquifer water supplies, even before considering social acceptability or legal or political implications. However, the additional research described above could identify other viable MAR schemes for Loreto, which could then be compared to other alternatives within the dynamic MCA framework.

Further Considerations

In addition to the urban and domestic use considerations in this project, agricultural water use should be taken into account when optimizing overall local water usage. Based on a CONAGUA report from 2005[9], 40% of the water extracted from the SJL aquifer is used for agricultural purposes. And although tourism growth is shifting water demands away from agriculture and increasing the importance of urban water conservation and management, agriculture remains a significant concern for the near term. For this analysis, we assumed that the 40% agricultural water use portion translates into a 40% contribution to the SJL overdraft. Therefore, by encouraging implementation of high water use efficiency in agriculture, it may be possible to achieve significant savings and significantly reduce the total aquifer overdraft. Despite the lack of municipal jurisdiction, a COTAS could initiate an effort to advocate for solutions on a local level. As an independent council designed to provide a bridge between government and local water management, a Loreto COTAS could act as an important intermediary of the necessary cooperation between competing water uses.

Recent statements by the FONATUR representative of Loreto, indicate that agriculture may also be responsible for a portion of the water currently considered lost through inefficiencies on the urban and domestic side[47]. Further investigation is necessary to establish whether this is the case.

While the impact of certain potential changes in circumstances that affect water management can be anticipated or even expected, others may be more significant and provide very different priorities. One particular example is climate change.

Climate change should not be excluded from municipal planning and management, given potential impacts and current global trends. Groundwater management is no exception. While an estimate of long-term climate effects on Loreto's water resources is beyond the scope of this project, literature provides useful insight to impending challenges.

A number of studies have modeled the potential climate change impacts in México, both regionally and nationally[48,49,50,51]. The two most recent of these provide smaller-scale spatial resolutions enabled by improved modeling capabilities, to allow for specific predictions of climate impacts on the Baja California peninsula. The studies consistently predict that the Baja Peninsula will experience the largest temperature increases in México—as much as 8°C by 2050[51]. However, the results are widely divided on climate change effects on precipitation. Overall, however, the Baja Peninsula is considered highly vulnerable to exacerbation of existing water deficiencies and desertification[49,50].

While these climate change predictions provide no basis for specific management measures in Loreto, they do justify a significant degree of caution. With such high levels of uncertainty, an adaptive approach is critical. This argues for employing a flexible and dynamic decision-support framework such as that developed for this project. In addition, our rigorous analysis of strategies for sustainable management for this project provided the foundation for a number of specific recommendations to help guide decision-making in Loreto.

Recommendations

Through the research and development of this project, we identified a number of opportunities to encourage sustainability in addressing the multi-dimensional freshwater challenges in Loreto. Following are the recommendations that emerged:

Prioritize demand-side measures

Our MCA results showed that demand-side measures should be prioritized in freshwater resource management in Loreto. Infrastructure upgrades, and conservation measures such as education and domestic fixtures should take precedence over new water supply projects.

Implement an aggressive conservation program

Conservation should be a critical component of any water management program in Loreto. The program should target children and community members, as well as tourists, through a media and advertisement campaign, community outreach, and water conservation awareness initiatives in schools. In addition, a financial incentive component should provide rebates to Loretanos for the installation of water efficient fixtures in existing households.

Implement a conservation policy for new developments

The most recent sizable development in Loreto, the Loreto Bay Company project, included water-efficient domestic fixtures in homes in conjunction with other conservation measures. Given the findings of the MCA analysis which support this initiative, we recommend that a new policy be developed and codified to ensure similar practices for all future development projects.

Use the MCA as a decision-making tool

The dynamic MCA framework developed through this project can be a critical tool for water managers and/or a Loreto COTAS to guide decision-making and justify water management recommendations. The MCA can be recalibrated to reevaluate the identified alternatives, or incorporate new alternatives, when additional information—e.g. better aquifer studies—becomes available or as circumstances change over time.

Create a Loreto COTAS
Given the high level of interest in politics and the environment in Loreto, a COTAS is the best opportunity to overcome the discontinuity that results from the political status quo. Further, introducing a means for the community to actively participate and influence the decision-making process can provide a sense of ownership over the outcomes of decisions, and thus inspire more effective management.

Implement an environmental assessment process for desalination project approval
Given the high degree of potential impacts compared to other possible measures to augment water supplies, a formal review policy is warranted to balance the benefit of reliable freshwater supplies against the costs in environmental impacts, particularly on the Loreto Bay National Marine Park and energy use from the isolated BCS energy grid.

Consider renewable energy-powered desalination
With sufficiently large population growth, a large desalination plant will be inevitable to provide adequate freshwater supplies for residents. If this becomes the case, renewable energy-powered desalination should be considered. Although the upfront investment costs are higher, these can be offset by lower ongoing operation and maintenance costs.

Assess agriculture water usage
The 40% of water extracted from for agriculture purposes contributes to the overdraft of the SJL aquifer. Therefore, policies that address this substantial portion should be considered. In particular, consideration should be given to measures to track actual water use and enforcement of high use efficiency technologies.

Solicit a comprehensive aquifer study
The MCA analysis depends highly on the estimated overdraft, in particular future scenarios that maximally magnify the degree of expected overdraft. However, the studies make very different assumptions of the SJL aquifer state, geological characteristics and water balance. A comprehensive assessment could provide a more detailed understanding of the hydrogeology to enable a better estimation of sustainable yield. Additionally, it could help assess the feasibility of other aquifer recharge options.

[Re-]Consider water tariffs

The fixed rate tariffs do not provide a strong incentive for conservation. Increasing tariffs or changing the structure of tariffs to reflect actual use can supplement conservation efforts. The most effective conservation programs, and those that achieve the desired results in shorter timeframes, are tied to usage-based water tariffs.

Conclusion

Like many arid regions around the world, Loreto faces water supply challenges, with concerns growing due to expected tourism-related population growth. Currently, the sole source of fresh water supply to the population of 12,000 is the San Juan Bautista Londó aquifer. The aquifer is already impacted by significant overdraft due to a combination of factors including high distributional losses, domestic overuse and ineffective supply management. As a result, seawater desalination is presumed to be the primary solution because of the supply reliability and high water quality that it can provide. However, our analysis found that desalination is a suboptimal short-term solution for Loreto for several reasons, including dramatically higher costs and energy use, as well as the potentially detrimental impact on the sensitive and ecologically unique LBNP that underpins Loreto’s tourism-based economy.

To assess the opportunities for more optimal water management strategies for Loreto, we first developed an MCA, which allowed us to evaluate water supply- and demand-side alternatives based on locally-relevant decision-making criteria. Overall results from the MCA showed that water demand measures should be prioritized by decision makers in Loreto, taking precedence over projects to secure additional freshwater supplies, such as desalination. More specifically, infrastructure upgrades and conservation programs should be given priority at all population levels, whereas water-saving domestic fixtures should be implemented in future population scenarios.

Equally important to our project goal of developing strategies for sustainable water supplies and management was the development of a flexible and dynamic decision-making framework. As circumstances change over time in Loreto or additional information becomes available, the MCA can be modified to reflect the new conditions and the preferences and objectives of actual decision makers.

While the MCA will help to improve the basis for decision-making, existing political factors may impede effective implementation of the MCA framework and limit optimal water management overall. We therefore identified and discussed a number of factors that contribute to the complex problem of water management in Loreto and addressed the most tractable concerns, specifically the high turnover and systemic discontinuity that results from the political status quo.

We proposed the implementation of non-profit technical groundwater committees, COTAS, provided for by Mexican National Water Law, as a potential means of overcoming discontinuity within water management in Loreto through community-level involvement. Given the strong community support and advocacy for more sustainable practices, COTAS offer Loretanos an opportunity to effectively influence local water management decision-making in the best interests of the community. We also see the MCA framework developed through this project as a critical tool for a Loreto COTAS to guide decision-making and justify water management recommendations.

The process of this project enabled us to provide key recommendations for our client, Eco-Alianza, to advocate for more sustainable water supply and management in Loreto. To overcome high inefficiencies and overuse in the water-limited environment of Loreto, water resource managers should implement intensive demand-side measures before turning to desalination to increase water supplies. If desalination becomes inevitable to meet freshwater needs, projects should be carefully reviewed to minimize impacts to the environment and community. Additionally, local activism in Loreto should be funneled through non-profit technical groundwater committees to drive more sustainable water management decision-making in the social and economic interests of the community. Finally, applying the dynamic decision-making tool developed in this project can guide water management in the face of diverse challenges and competing priorities, in order to satisfy both current and future population needs. By developing and carrying out the education programs for conservation initiatives, and encouraging implementation of the other strategies, Eco-Alianza can further its mission to promote sustainable use of natural resources and stewardship of the environment on behalf of the local community.

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