How to Distribute Water Fairly in Times of Scarcity

A Participatory and Simulation-Based Process
towards Distribution Policies for Guadalajara's Aquapheric
with a Distributive Justice and Deep Uncertainty Approach

TU Delft

Master Thesis Project
Engineering and Policy Analysis, TU Delft
Ariel Goldin Marcovich, 2024

OHIPPO

Escuela de Gobierno y Transformación Pública
Tecnológico de Monterrey

CIENCIA DE DECISIONES

To Andrea for your unconditional support.

How to Distribute Water Fairly in Times of Scarcity

A Participatory and Simulation-Based Process
towards Distribution Policies for Guadalajara's Aquapheric
with a Distributive Justice and Deep Uncertainty Approach

By

Ariel Goldin Marcovich

To obtain the degree of Master of Science at the Delft University of Technology
to be defended on the 27 of August 2024

Student Number	5356717	
Project Duration	January 2024 to August 2024	
Thesis Comitee	Prof.dr.mr.ir. Neelke Doorn	TU Delft, Chair
	Dr. Jazmin Zatarain Salazar	TU Delft, 1st Supervisor
	Dr. Edmundo Molina Perez	Tecnológico de Monterrey, External Supervisor

This research project was conducted as part of the Hyper-heuristics for Interpretable Public Policy Analysis Research Laboratory (HIPPO Lab) of the Technology, Policy and Management Lab of TU Delft. For the development of this Thesis, a participatory workshop was conducted in Guadalajara, Mexico in April 2024 at the Campus Guadalajara of The Tecnológico de Monterrey University. This workshop was conducted thanks to the financial, material, logistical and technical support of the following institutions from El Tecnológico de Monterrey: the School of Government and Public Transformation, The Centre for the Future of Cities, and the North and East Regional Directorate.

Data and Availability

The following digital resources were developed as part of this research:

- The **mock-up of the Decision Support Tool for Distribution Policies of Guadalajara's Aquapheric** can be found at: https://gdl-aqp.streamlit.app/
- The **Scenario Exploration Tool** used to facilitate a justice-centred discussion at the Justice Exploration Workshop can be accessed at: public.tableau.com/app/profile/ariel.goldin.marcovich/viz/HerramientaAcuafericov3
- The **Python Repository** used for the development of this thesis can be found at: https://github.com/arielgoldin/GDL_Aquapheric_Policies

Executive Summary

The city of Guadalajara, Mexico, is facing increasing challenges in supplying enough water to its five million inhabitants. To adapt the city's water supply system to worsening drought conditions, some key vulnerabilities need to be addressed. The city's water supply system is compartmentalised, meaning that each one of its four main sources supplies a specific area of the city. Thus, if one source underperforms, one area of the city will not have enough water, and the other sources cannot compensate. This situation happened in 2021, when one of its sources reached critical levels leaving around 500,000 inhabitants without water supply for over 3 months. To combat this vulnerability the city built the Aquapheric: a circular aqueduct that interconnects the supply areas and can pump up to 1m^3/s in both directions in each segment independently. However, the government has not developed a distribution policy for this infrastructure.

This project proposes a participatory and simulation-based process for designing a Decision Support Tool (DST) that could serve as the basis for a Distribution Policy for the Aquapheric. Such policy would determine how much water should flow in each segment of the Aquapheric under the current drought conditions based on a set of objectives selected by policymakers. The pool of objectives available was defined via an in-person participatory workshop that was conducted with over 26 members of the local government and academia. The Distributive Justice Principles framework was used to guide the ethical discussion during the workshop and to develop the mathematical formulations of the objectives. A problem formulation for a Multi-Objective Optimization algorithm was designed to find the best performing and best compromise policies for the objectives that policy-makers select on the DST.

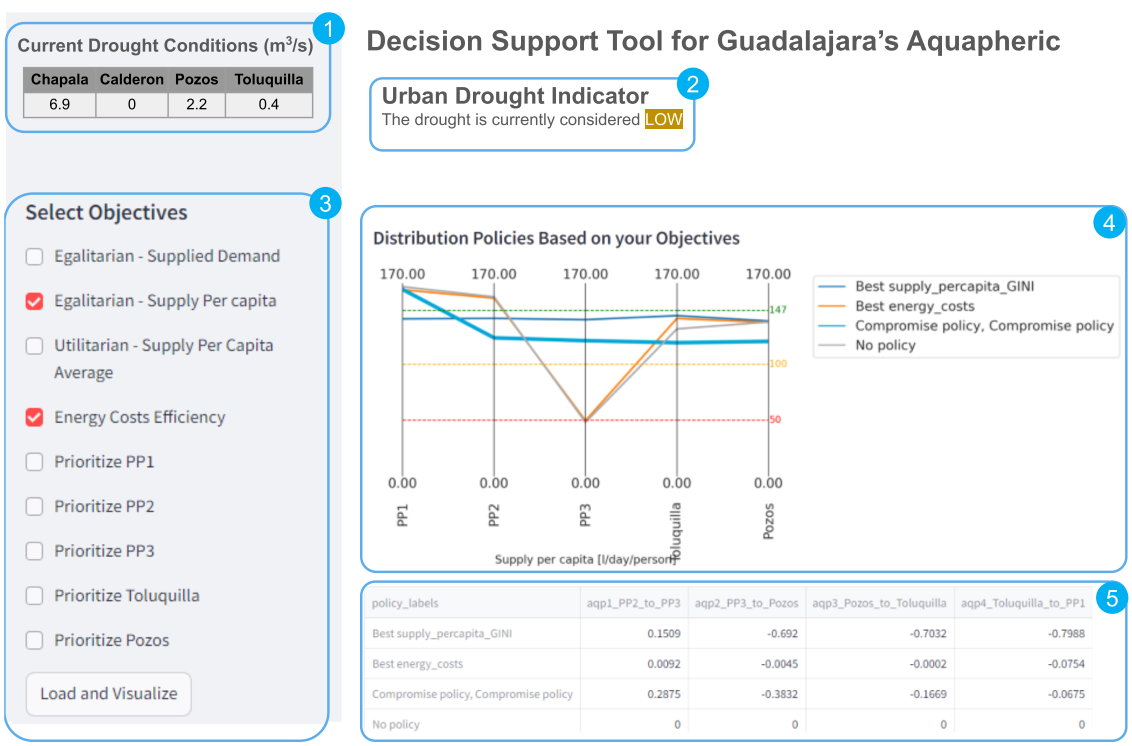


Figure 1. Mock-up of the Decision Support Tool for Guadalajara's Aquapheric

A mock-up of this Tool was developed and is available online and has the following 5 components (**Figure 1**):

1. The input data of the DST is the water flows available for each one of the four sources of water of Guadalajara. This set of flows is referred to as **drought conditions.**
2. For these drought conditions, the DST estimates if the drought should be considered low, mid or high based on a purpose-made **Urban Drought Indicator.** The concept of this indicator was proposed during the workshop by policymakers who argued that the objectives of the distribution policy should vary as drought intensity increases. The indicator was defined using a logistic regression scenario discovery based on some of the assumptions behind some formulations that were mentioned in the workshop.
3. The policymaker can now, informed by the drought intensity, select a set of objectives that should guide the distribution of water in the city. The available set of objectives is a result of the literature on Multi-Objective Optimization using the **Distributive Justice principles** as well as the **participatory workshop** conducted as part of this project.
4. The DST conducts an optimization using a **Multi-Objective Optimization Algorithm** for the current drought conditions using a fixed optimization formulation. The set of objectives selected by the policymakers is used to filter the optimal policies resulting from the optimization and not necessarily as part of the optimization formulation. Thus, the **best performing policy** for each individual objective selected, as well as the **compromise policy** for all the selected objectives is presented. The policymaker can visually inspect the proposed policies and change the objectives if necessary.
5. Once a preferred policy is selected, the exact **water flows** for each segment of the AqP can be extracted and implemented in the infrastructure.

The research was conducted in three stages. An initial Participatory Formulation Stage provided a diversity of possible interpretations and operationalization of justice as well as other considerations necessary to develop the optimization framework. In the Experimentation and Optimization stage, the final formulation and hyperparameters of the optimization algorithm were defined as well as the Urban Drought Indicator. The final Decision-Support Stage integrated the learnings and results of the previous two stages to develop the DST designed to guide policymakers in selecting distribution policies for the Aquapheric with a justice approach.

Future projects could use this DST to conduct an Interactive Policy Evaluation workshop to determine what objectives should be used under what conditions. This protocol in conjunction with the DST would become the overarching Distribution Policy for Guadalajara’s Aquapheric. Future research could also refine how this Policy could be integrated with the rest of the water management policies such as those related to water sourcing, distribution and usage as well as watershed management. Such integration, considering Guadalajara’s recurring cycle of drought, is referred to in this research to as Comprehensive Water Scarcity Management.

The theoretical discussions in this research focus on how deep uncertainty, particularly that related to values, can be tackled by offering tools based on simple models, built with participatory knowledge co-creation processes and that enable learning and flexibility as opposed to robustness.

Preface

I want to start by thanking Jazmin Zatarain, whose trust and guidance made this project possible, as well as Neelke Doorn and Edmundo Molina who quickly got excited about this project and supported me along the way. Additionally, I want to thank everyone that made the workshop conducted in this thesis a reality: the organising committee, Edmundo Molina, Steven Popper, Azucena Rojas and Roberto Ponce; Jose Antonio Torre and the Centre for the Future of the Cities for providing financial support for the flight to Mexico; Ale Ayo and Julian Somoza for championing participation from the local government and sharing their vision for the future of drought management in Mexico; Carlos Aguirre, Hector Chaires, Margarita Castrillo, Carlos Torres and Gabriel Montaño for ensuring the participation of the CEA and SIAPA; and the workshop volunteers Andrea Martinez, José Sánchez, Megan Montaño and Moni Carrillo.

I also want to thank my family, Andrea for your care and support throughout my life and particularly in the last stage of this thesis, Daniel for pushing me to always follow and nurture my curiosity and dive into complexity, Karen for all your efforts and support to start and finish this Masters, Gabi for your feedback and pushing me forward, Pablo for your clarity and helping me settle in this new city, and Theo for making me want to come to the Hague and enjoying it with me; Valentina, por tu amor, apoyo, escucha, compañía y creer en mí siempre; Kata and Simon for making me feel at home in these flatlands and caring for me along the way; my friends from Mexico for making me who I am; my friends in the Netherlands, Agathe, Antoine, Angela, Fotini and Philip for sharing this amazing experience full of learning and adventures; Lea and Jona for building a home with me that we can now take anywhere; Ludwig, Ryan and Alex for teaching and learning with me more than anyone; Laura Kuri for teaching me the importance of facilitation; Fabio, Claudia, Tadzio, Vico and Luciano for caring and supporting me always; Alvaro Soldevilla, Jessica Torres and Laura Durán for starting this journey with me back in 2021; Arnoldo Matus, Abril Cid and Emilio Rodríguez Izquierdo for shaping who I am as a professional and developing my approach to policymaking for climate change adaptation; and to Eduardo Batllori for sharing his passion for water and pushing me to devote my career to it.

Ariel Goldin, 2024

Table of Contents

Figures

Tables

Acronyms

AqP	Aquapheric
DJP	Distributive Justice Principles
DST	Decision Support Tool
GDL	Guadalajara
MOEA	Multi-Objective Evolutionary Algorithm
MOO	Multi-Objective Optimization
SA	Supply Area

1. Introduction

1.1 The Decision-Making Problem

Guadalajara is Mexico's second-largest city with over five million inhabitants. Due to worsening droughts, increasing population and ageing infrastructure, the city faces increasing challenges in supplying enough water to its population and growing economy (IMEPLAN, 2020). The city's water distribution system is divided into five Supply Areas (SA). Each of these areas is associated mainly with one of the four superficial or subterranean water sources (**Figure 2**). Because the system is compartmentalized, if one of the sources underperforms, a region of the city will be left with no access to the municipal water supply. This is what happened in 2021: a severe drought caused the Calderon dam to reach critical levels and had to be shut down, leaving around 500,000 city dwellers with no water supply for more than 3 months (R-Cities, 2022).

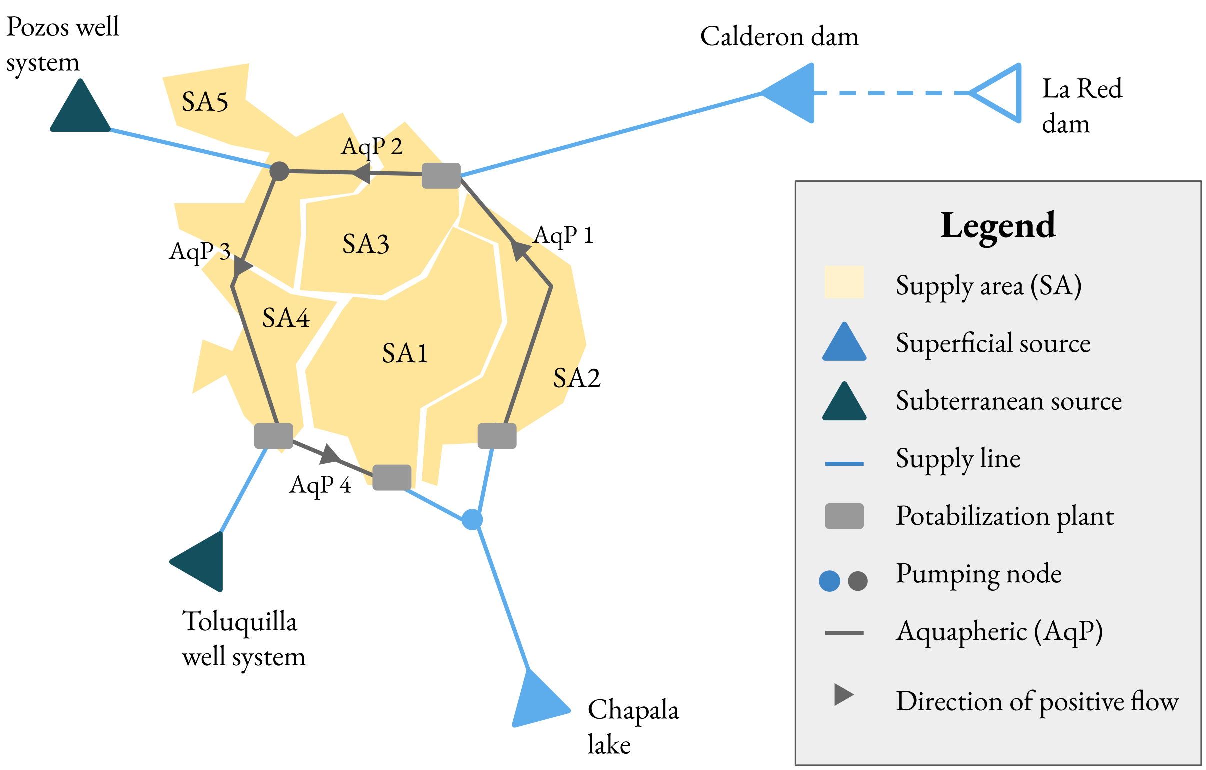


Figure 2. Guadalajara's urban water supply system schematization

In 2022, as a response to this vulnerability, the Government built the Aquapheric (AqP): a circular aqueduct that interconnects the five supply areas and can pump up to 1 m^3/s of water in both directions in each of its four segments independently. By balancing the supply in all five areas, this infrastructure can significantly increase the city's resilience to drought events. However, an operation policy for this infrastructure has yet to be developed.

During drought, the AqP can be used to distribute the available water within the city. But how should this distribution be implemented? According to which values should the normative and legal principles governing Guadalajara's AqP be drafted? The legal framework has not yet caught up with the new infrastructure and hydroclimatic conditions, and the normative principles for water distribution for this type of boundary scenario haven't been agreed upon or even widely discussed (A. Ayo, personal communication, November 13, 2022).

In addition to these value-related challenges, there are significant uncertainties about the system's current and future structure and behaviour (R-Cities, 2022; SIAPA, 2014). On the one hand, in part due to underfunding, the water authority doesn't have the capacity to monitor with high accuracy key variables of the system, such as the water consumption per supply area, the grid's efficiency and the amount of water that is being extracted by decentralized well systems (R-Cities, 2022). On the other hand, the city is proposing a wide variety of measures to ensure future supply - such as rainfall harvest, the construction of a new dam, grid renovation, incorporation of new supply areas and water reuse plants - but it is still uncertain when they will be implemented, at what scale and what impact will they have (R-Cities, 2022).

The complexity of this decision-making problem is further accentuated by constraints on the water distribution that would be made possible by using this infrastructure (**Figure** 3). Firstly, due to the physical and technical characteristics of the system, it is only possible to displace a maximum amount of $1m^3/s$, and due to an excessive altitude differential, it is not currently possible to pump water between the SA5 - Pozos and SA4 – Toluquilla. Secondly, there are political frameworks and agreements that specify minimum or maximum amounts of water that must be supplied to certain areas. Finally, this infrastructure only determines how much water reaches the central distribution system of each area, but the water authority cannot further specify who gets how much. Since the population and economical activities within each area are highly heterogeneous, this limitation significantly frames how justice considerations can be conceptualized.

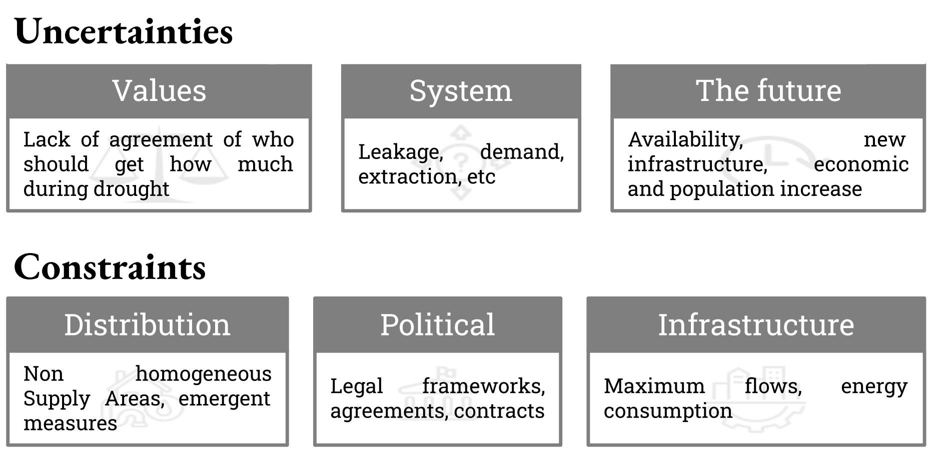


Figure 3. Summary of uncertainties and constraints of the decision-making problem.

The combination of uncertainties about the system's current and future state, as well as the lack of agreement on the values of stakeholders around a policy problem, is defined as deep uncertainty (Walker et al., 2013). As drought becomes more frequent, intense, and long-lasting, the appropriate use of the AqP will be determinant on the social and economic impacts of this weather phenomenon on this highly populated and vulnerable metropolis. This policy problem is characterized by a deeply uncertain and complex decision arena with potentially high consequences for the people living in Guadalajara. As such, it is a problem with high societal relevance and is pertinent for a Master's Thesis on Engineering and Policy Analysis.

As in any urban water distribution system, an operation policy for the AqP should respond to the city's values in order to distribute the available water to the population in the best way possible, despite the system's uncertainty (Lempert et al., 2003). Additionally, the operation policy should be able to incorporate future changes to the system, so as to remain useful in the mid to long term future. To develop such a policy, an innovative Decision Support Tool (DST) based on Multi-Objective Optimization (MOO) with a justice approach derived from a participatory process is proposed. As further detailed in Section 2.3, there are little to no scientific publications that propose DMDU methods for drought management in cities that incorporate a justice approach. This case is thus an opportunity for a relevant scientific contribution to this growing field of knowledge.

1.3 Knowledge Gap

This research is framed within the water-related DMDU field of knowledge. Four literature reviews were conducted in Web of Science to assess the knowledge gaps that this research aims to address (see queries and results in Appendix 1). The literature reviews align with this thesis's main topics: a) DMDU for drought management; b) Justice incorporation in water-related Multi-Objective optimization; c) Participatory methods for MOO problem formulation; d) DMDU in Mexico. Additionally, a query was conducted to find publications in the intersection of the main topics (excluding Mexico and DMDU) to assess the novelty of this project the Mexican context.

As pointed out by Zeff et al. (2016), DMDU for water supply often focus on long-term infrastructure sequencing but neglects short-term management decisions (management and operation). Indeed, DMDU research often favours planning over management and operation. This asymmetry offers a highly relevant research opportunity both to develop the management side of DMDU and to incorporate DMDU into drought management.

This research specifically focuses on methods to incorporate justice considerations into drought management with a participatory and optimization-based approach. At the intersection of these topics, there was only one project found: the novel framework Equitable, Robust, Adaptive, and Stable Deeply Uncertain Pathways (DU Pathways$_{ERAS}$) proposed by Gold et al (2023). This framework bridges planning and management, by including justice considerations and conceiving stakeholder involvement. It has been applied for designing policies to transfer water between water utilities of cities such as Durham, Raleigh and Chappel Hill in North Carolina (known as the Research Triangle), as well as water allocation in the Colorado River Basin (CRB) However, no application of such a framework or similar ones outside the Research Triangle in the United States or the CRB has been found. Additionally, no application of the framework has been found that focuses specifically on water distribution inside a city as opposed to between cities.

Additionally, this research will rely on a participatory process to include considerations about justice which was not considered in the DU Pathways methodology. This research approach has been signalled as highly valuable in the context of multi-objective optimization (Afsar et al., 2023; Yang et al., 2023) and for decision-making in complex environmental problems in complex multi-actor decision arenas with contrasting and even non-explicit values (Moallemi et al., 2023). Although there are documented experiences of using participatory processes in MOO projects, there's still significant space for making scientific contributions in this area, particularly for MOO projects using a Distributive Justice Approach.

1.4 Research Questions

Considering the knowledge gap detailed in the previous section, we can formulate the following research question and sub-questions that will guide this research project. Each of these sub-questions will be tackled in one of the three main sections of this thesis as described in the next section.

RESEARCH QUESTION

***RQ*. How can we design distribution policies for Guadalajara's Aquapheric to ensure just water distribution during drought?**

SRQ1. How can local stakeholders be engaged in the process of identifying how fairness should be interpreted and operationalized for water distribution under drought conditions?

SRQ2. What optimisation problem formulation can reliably find optimal policies for different objective formulations and drought conditions?

SRQ3. How can we support the selection process of optimal distribution policies by the local authorities considering value and system uncertainties?

1.5 Research Outline

This research project has three main stages associated with the three research questions (**Figure 4**). For each section, the conceptual framework, the research methods, and the results are presented. The first stage, Problem Formulation, includes the participatory workshop and the Optimization Model development. This stage is designed to produce a variety of objective formulations and restrictions that will be later used for experimentation. Next, the Experimentation and Optimization stage includes a simple validation of the model, an analysis to define what problem formulation to use, as well as the development of an Urban Drought Indicator. Finally, in the last stage, a Decision Support Tool that uses the optimization setting resulting from Stage 2 and the insights from Stage 1 is designed. The final product includes a mock-up of a Decision Support Tool that allows policymakers to explore how different sets of objectives translate to distribution policies. This Tool could be used in future participatory processes to define what objectives should be used for water distribution under what drought conditions.

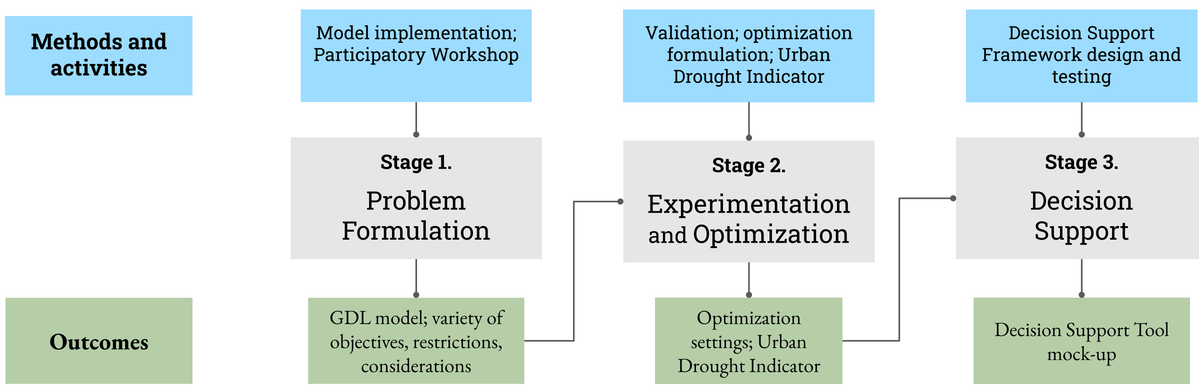


Figure 4. Stages of the research

1.5.1. Problem Formulation Stage

In the context of Multi-Objective Optimization, problem formulation is defined as the process of identifying a set of objectives to be minimized or maximized, a set of constraints and a set of decision variables (Afsar et al., 2023). This is a process that is often iterative and evolves over time as validation processes, numerical experiments, and real-life applications are conducted.

This stage is designed to generate an ensemble of different problem formulations and restrictions that will be used in the next stage to explore the solution space. The reason why this stage is not designed to provide a single definitive problem formulation is two-fold. Firstly, this decision-making problem is complex, as it is characterized by deep uncertainty. Secondly, it is unique, as this infrastructure is new and not highly common in other cities, thus limiting the amount of available documented examples to guide the formulation for this problem. Therefore, it would have been unviable to aim for a convergent process considering the available resources for this thesis.

To develop this ensemble of objectives and to identify the relevant restrictions, a workshop was conducted in April 2024 that brought together over 26 representatives of the local government, academia and civil society. The design of this workshop was guided by the following three principles:

- **Structured**
  The design of the participation materials was guided by the framework proposed by Afsar et al., (2023) to systematically generate problem formulations. To further structure the justice exploration for this problem, the Distributive Justice Principles (DJP) and its operationalizations for MOO (Doorn, 2019; Rimon, 2023.; Znabei, 2023) was presented during the workshop and offered as a tool to the participants to frame their proposals of objectives.
- **Non-prescriptive**
  Despite the defined structure, participants were offered a considerable liberty on which objectives and restrictions they could propose, leaving space for ideas that were not initially considered by the authors of the Workshop. Different resources were accessible to the participants to guide their proposals such as indicators, a characterization tool and a Scenario Exploration Tool but the inclusion of additional resources was encouraged.
- **Non-convergent**
  Instead of aiming for a single agreed-upon problem definition, the participants were grouped in four non-sectoral tables each of which proposed their own formulation, effectively promoting and valuing diversity.

1.5.2. Experimentation and Optimization Stage

The objective for this stage is to conduct the necessary computational experiments to identify and validate the settings for the optimization algorithm that will be used for the final Decision Support Tool. This stage is particularly important, as the design of the final tool implies that an optimization will be conducted every time the AqP needs to be used and the drought conditions have changed.

The proposed optimization approach differs to other commonly used methods used in similar problems where an adaptive policy that was optimized on a set of historical or synthetic data is then used to estimate flows for any input data. However, a distribution policy for the AqP should be able to deal with flows associated with any type of shock and stress for which no historical dataset will be sufficient. For example, in June 2024, the pumping system of the Chapala Lake, the main source of GDL, was critically damaged due to grid instability. This situation has never happened before, but the AqP should have been able to deal with it. Thus, the proposed solution requires that an optimization is run for the current available water flows from the sources every time that a decision needs to be made. Additionally, some of the experiments were conducted for the complete space of the possible scenarios, not only the likely ones based on historic data.

Additionally, the decision support approach requires that decision-makers are able to quickly explore how different justice objectives can be used to define distribution policies. Thus, the experiments were designed to ensure that the optimization algorithm can find optimal policies for any drought scenario and combination of objectives in a reliable a quick way. The experiments conducted can be grouped into the following three stages:

- **Settings for a reliable and efficient optimization**
  To ensure that the algorithm can perform unsupervised optimizations for all the possible drought conditions the following questions need to be addressed:
  - What is the smallest **number of function evaluations** (nfes) that can ensure that the algorithm converges for all the drought space?

- What is the maximum value of **epsilon** that can ensure that the policies found do approach the global maxima for each individual policy and objective combination trade-off policy?

- **Optimization formulation definition**
  As mentioned by Znabei (2023), justice considerations can be incorporated in MOO by introducing justice objectives in the optimization or by filtering the optimal policies (called Pareto Front) to find policies that reflect justice objectives. This second approach is known as a-posteriori. To choose a final optimization formulation, it is necessary to ensure that the specific formulation of the optimization can provide the desired policies for a wide variety of objectives. To do so, a comparison of a-priori, a-posteriori and a mixed formulation for three representative scenarios was made to find the minimal set of objectives that, can provide policies with the desired performance.

- **Assumption-based Urban Drought Indicator**
  During the workshop, two tables signalled that the AqP should change its function in relation to drought intensity. However, there are no existing drought indicators that could be used for this specific problem as we focus on urban water scarcity rather than on precipitation deficit. During the workshop, one table suggested that if drought was low, mid or high the city should strive to ensure that every SA would have at least 142, 100 or 50 l/day/person respectively. Based on this assumption an Urban Drought Indicator was defined as the drought conditions under which it would be most likely that at least one SA would fall below these thresholds despite any possible distribution using the AqP.

1.5.3. Decision Support Stage

The results and insights from the two previous stages were integrated into the design of a Decision Support Tool (DST), composed of conceptual and technical elements to support the process of designing and selecting distribution policies for the AqP. The mock-up of this Tool can be used by decision-makers to explore how different sets of objectives can be translated into distribution policies. This mock-up is currently available online[1] and could be used in a second workshop to define which objectives should guide the selection of a distribution policy under what conditions.

The DST first estimates the drought intensity considering the current available flows of the four water sources. Drought intensity is calculated by the Urban Drought Indicator. The indicator was built following a proposal made during the workshop about how the objectives behind the distribution policy should vary depending on whether the drought is considered to be low, mid or high (Section 4.2.1). Thus, policymakers could choose what set of objectives to use depending on the output of the Urban Drought Indicator.

A Multi-Objective Optimization Algorithm generates a set of optimal policies using the problem formulation derived from the Experimentation Stage (Section 4.2.4). Then, the user can select a set of objectives to filter the optimal policies in order to find the best-performing solution for each objective and a compromise solution for the set of objectives. This approach, called a-posteriori, was selected as it has been proven efficient in terms of finding optimal policies for some justice-related objectives in the literature (Shavazipour et al., 2021; Znabei, 2023) and in the experimentation stage of this thesis (Section 4.2). Additionally, by avoiding the need to conduct

[1] https://gdl-aqp.streamlit.app/

an optimization each time the set of objectives changes, the a-posterior approach enables rapid exploration of potential objectives.

The objectives available for a-posteriori filtering were first developed based on literature that has laid down the theoretical ethical basis for the DJPs and the mathematical formulations for Multi-Objective Optimizations (Rimon, 2023; Sarva et al., 2021; Znabei, 2023). Then, the objectives were further operationalized and selected based on the results of the workshop that produced a set of 9 objectives with a combination of DJP, indicators and an economic objective.

The overall design of this DST favours flexibility over robustness by optimizing each time drought conditions change, and a distribution policy is needed. This approach was favoured over others such as Direct Policy Search where a single optimization produces an adaptive policy that could determine the AqP flows for any drought conditions. This approach enables us to find solutions and optimal policies for each drought state with higher certainty than an approximator trained for all the possible drought conditions. Additionally, it allows for faster learning cycles by giving the tools to the users to explore alternative policies.

The DST could be used in subsequent knowledge co-creation stages such as an interactive policy exploration workshop to define a Distribution Policy that includes what objectives to use under what conditions. This Policy could ensure transparency in the decision-making behind water distribution for a city advancing towards a more just and drought-resilient system. The Distribution Policy could be periodically updated using this same DST or future versions of it to incorporate learned experiences and new knowledge as a means to deal with uncertainty related both to the system and to the values around urban water distribution.

2. Theoretical Framework

Decision-Making Under Deep Uncertainty (DMDU) is the body of knowledge focused on making decisions in policy arenas characterized by deep uncertainty (Marchau et al., 2019). Deep uncertainty occurs when there's a lack of knowledge or agreement on the likeliness of future scenarios, the impacts of possible interventions, the values around preferred outcomes and the structure and behaviour of the system of study (Walker et al. 2013).

2.1 Managing Drought Under Deep Uncertainty

In a very broad sense, drought is defined as a deficit of water in relation to habitual conditions. Mishra & Singh put forth four categories of drought, depending on the causes of the deficit of water and its intended uses.

- **Meteorological drought**
  Defined as a deficit in precipitation over a certain region. This can be caused by changes in the interannual weather, such as ENSO cycle, changes in the long-term climate, such as those generated by climate change, and those generated by changes in precipitation patterns due to changes in the territory, such as deforestation.
- **Hydrological drought**
  Defined as the deficit of surface or subsurface water. These can be caused by a meteorological drought, changes in management, land cover, evapotranspiration rates and other phenomena that affects how water flows and is stored in on land and underground.
- **Socioeconomic drought**
  Defined as a deviation of a water system's capacity to meet water demand. This can be caused by shocks and stresses to supply, such as dam closures, aqueduct failure, river dryness, etc. Or by shocks and stresses to demand such as demand spikes, or urban and economic growth.
- **Agricultural drought**
  Defined as a deficit in soil moisture and consequent crop failure. This can be caused by changes in rainfall patterns (both in quantity and seasonality) and changes in temperatures that can increase evapotranspiration.

In this project we aim to find the best distribution policies based on available flows of GDL's water sources. The specific causes of this deficit of water supply or increase in water demand are not relevant for the nature of the desired distribution. Therefore, we focus on socioeconomic droughts. Other categories of drought can be relevant for other components of drought management, such as reservoir control, but are outside the scope of this thesis.

Managing drought has been the focus of several DMDU publications as drought is considered "one of the most complex of all natural hazards" (Wilhite, 2009) due to its hydroclimatic causes as well as its social implications. In this body of literature drought management within DMDU is tackled be either robustness-oriented or adaptive planning methods.

The majority of publications in this research field focus on robust policy-making, understood as policies that work as best as possible in a large proportion of possible futures (J. H. Kwakkel et al., 2016). Most of these publications use some variation of Multi-Objective Optimization (MOO). Some of the most notorious examples include portfolio planning for regional cooperation (Lau et al., 2023; Trindade et al., 2017), single-city water supply (Kasprzyk et al., 2009) and reservoir modelling (Marton & Knoppová, 2019). Others focus on explorations of specific aspects of robust decision-making such as scenario neutrality (Quinn et al., 2020), multistakeholder robustness beyond optimality (Herman et al., 2014), cooperative stability and power relations (Gold et al., 2022) and probabilistic decision analysis (Lanzanova et al., 2019).

Publications about adaptive policies are the second largest proportion of the literature that refer to drought within DMDU. This DMDU approach refers to policies that include mechanisms to modify the interventions after the initial implementation based on how the future unfolds, considering the uncertainties about the future and the impacts of the proposed interventions, (J. H. Kwakkel et al., 2016). Miro et al., (2021) propose an adaptive framework that relies on novel machine-learning techniques for groundwater modelling which is usually one of the biggest sources of uncertainty in water supply planning. As in most adaptive policies within DMDU, some publications focus on investment pathways (Popper et al., 2019). However, a series of sequenced publications were found that developed a framework to bridge management and planning decisions for drought management. All of these publications are applied within the context of regional cooperation, focusing primarily on vulnerability (Trindade et al., 2017), cooperative stability (Lau et al., 2023) or reliability based on risk-of-failure (Trindade et al., 2020).

Finally, the latest publication from that same series presents a framework that integrates robustness, adaptability and equitability applied to both water management and water supply planning under drought (Gold et al., 2023). This publication was the only one that had an explicit justice approach to drought management under DMDU and thus was the main guideline to build some of the methods proposed in Section 3.

2.2 Distributive Justice for Water Allocation

Gold et al. (2023) is the only found that publication that deals with justice in the context of urban drought management within DMDU (Appendix 1). Thus, to explore the literature around this topic, the search was broadened to include the larger body of research that deals with justice within DMDU applied to urban water management.

The definition of justice is subject to significant academic discussion (Doorn, 2019). In this study, we will use the most intuitive and simple definition which is that justice relates to "the right thing to do" (Doorn, 2019). Precisely because this definition is imprecise, one of the main objectives of this thesis is to identify, via knowledge co-production and experimentation, what is *the right* way of distributing water during drought using the Aquapheric. The thesis will continuously use this approach of leveraging intuition and striving to formalize it through exploration and experimentation.

Within the urban context, some authors focus on justice considerations for intermittent supply systems, that is systems where there is no continuous supply mostly found in the global south (Nyahora et al., 2020; Ramani et al., 2023; Solgi et al., 2020). These systems are particularly interesting for the case study because, whereas Guadalajara doesn't have an intermittent system under normal conditions, it has had it during drought (R-Cities, 2022). Applications to groundwater allocation were also identified (Hesamfar et al., 2023; Valipour & Ketabchi, 2023) which could also be useful as groundwater accounts for 30% of the city's supply (R-Cities, 2022).

A large body of literature tackles justice for water allocation through the operationalization of the Distributive Justice Principles (DJP). This framework is under a Consequentialist moral theory, meaning that the fairness of an action is judged by its consequences (Znabei, 2023). As these consequences can be assessed using models, the DJP are an accessible way of incorporating justice considerations into model-based decision-making. Other moral theories such as Procedural justice, where an action is deemed fair if it was developed via a fair process, are more difficult to incorporate into this type of model-based policymaking.

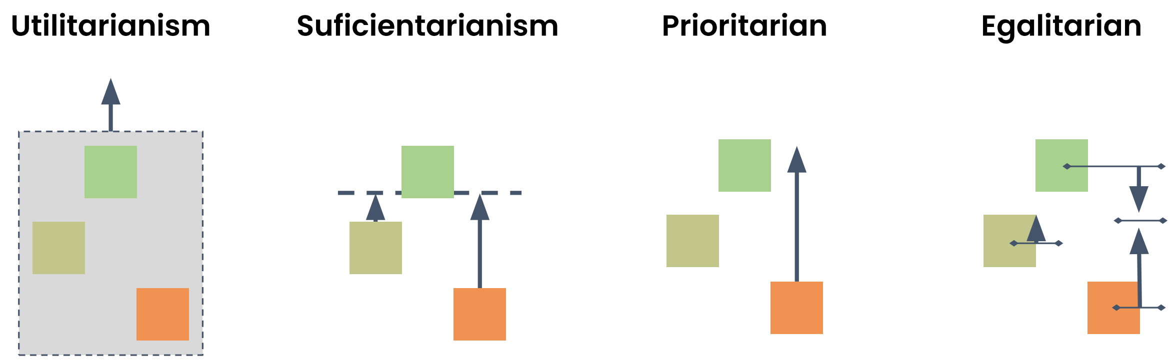


Figure 5. Distributive Justice Principles
Source: Modified from Zatarain-Salazar

In particular, there's a growing body of literature that has implemented DJP within multi-objective optimizations. The four principles (**Figure 5**) most commonly used are Utilitarian, Egalitarian, Prioritarian and Sufficientarian (Doorn, 2019; Sarva et al., 2021; Znabei, 2023). Other principles were not included as they are more complex, difficult to implement or less explored in the literature such as Low regrets. Finally, as further described in the next section, a-posteriori optimization was selected as it provides more flexibility as well as knowledge co-creation and learning opportunities.

The four distributive justice principles used in this project are summarized in **Table 1**. Each one of the principles interprets differently how the risks or benefits should be distributed and includes an operationalization from the literature. These principles are operationalized via the calculation of a justice indicator based on a performance indicator estimated or measured for each one of the parts, such as water *Supply per capita* (Section 3.2). Yang et al. (2023) further discuss the different operationalization approaches and highlight the role of participatory decision-making offering highly valuable insights for this study. The four principles used are the following:

> **Utilitarianism** is one of the most widely used theories of fairness (Sarva et al., 2021). It proposes that a fair distribution is where the benefits or risks are maximized for the biggest proportion of the parts. Under this conception, the focus is on the overall picture, and the differences between the parts are irrelevant. In most cases, this principle is operationalized using a simple or weighted sum of a utility function (Sarva et al., 2021; Znabei, 2023), but in this case the average of the performance indicators for the five SAs is used as no utility function was defined.
>
> **Egalitarian** principle, also often referred as equality, is where fairness is achieved when the difference between the parts is minimal. This is considered a comparative justice approach where a just distribution of any part depends on the distribution allocated to the others (Ciullo et al., 2020; Doorn, 2019). This approach has been criticized based on the levelling down objection, that is that it involves reducing the utility distributed to the parts that have the most to give it to the ones that have the least. This objection should be considered in how to an Egalitarian-based policy is implemented and communicated.
>
> **Prioritarian** principle states that available resources should be used to improve the conditions of the least well-off independently of those that have relatively higher conditions (Doorn, 2019). Even though this approach is very intuitive, it is difficult to define how to estimate conditions and it is unclear if only the least well-off should be prioritised even if there are some others that might be marginally better but could still need additional resources.
>
> **Sufficientarianism** principle states that there's a minimum threshold above which each part should be. Any other differences are not relevant. This approach can be highly relevant for the distribution of life-dependent utilities such as water (Doorn, 2019). For example, the World Health Organization suggests that every human requires between 50 and 100 l/day. Thus under the Sufficientarian principle any distribution where all the parts have more than 100 l/day/person would be considered fair.

More detailed descriptions on the ethics of distributive justice in water systems can be found in Doorn (2019) and detailed descriptions on the ethics of DJP in multi objective optimization problems in Znabei (2023). Additionally, there are more complex operationalizations of the DJP that incorporate non-linear utility functions (Sarva et al., 2021; Xinying Chen & Hooker, 2023) but they were not used in this thesis to reduce the set of assumptions and potential uncertainties in the model and to maximize explainability.

Table 1. Distributive Justice Principles for urban water distribution

Principle	Description	Limitations	Operationalization for MOO	Source
Utilitarian	Maximize or minimize the overall value of the performance indicators of the parts	Doesn't consider the diversity or inequalities between the parts	Maximizing average PI of the parts $$JI_u = \frac{1}{n}\sum_{i=1}^{n} PI_i$$	Modified from
Egalitarian	Reduce the difference between the performance indicators of the parts	Dealing with the parts that water is being taken from is complex. Doesn't recognize intrinsic inequalities.	Minimizing GINI coefficient $$G = \frac{\sum_{i=0}^{n}\sum_{j=0}^{n}\lvert PI_i - PI_j\rvert}{2n^2 PI_i}$$	(Ciullo et al., 2020)
Prioritarian	Maximize the level of the performance indicator of the least well-off part	Complex to define and measure the least advantaged population while also optimizing variations in the least advantaged. Current operationalisations include numerical assumptions.	$$W = \begin{cases} \frac{(u(x_i)-u(c_{zero}))^{1-\gamma}}{1-\gamma}, & \text{if } \gamma! = 1 \\ ln(u(x_i) - u(c_{zero})), & \text{if } \gamma = 1 \end{cases}$$ Where γ and c_{zero} are two constants proposed by Adler et al. (2017) that reflect ethical choices.	(Adler et al., 2017)
Sufficientarian	Ensure that all parts are above a certain threshold of a performance indicator	Does not define how to distribute water among the parts that are above or below the threshold	Minimizing the number of parts below the threshold	No MOO operationalization found in the literature

Note. These formulations were assembled and further discussed by Sarva et al. (2021) for the context of water allocation. The sources listed above are the original sources listed in that thesis.

2.3 Multi-Objective Optimization

Desirable solutions for complex decision-making problems often require the consideration of multiple conflictive objectives (Shavazipour et al., 2021). This means that there is no single optimal solution. Multi-objective optimization methods tackle this issue of conflicting objectives by finding solutions that are referred to as non-dominated or Pareto Optimal. The ensemble of optimal solutions cannot be improved in one objective without worsening the conditions for another. This ensemble of policies is called the Pareto Front or Pareto Set (**Figure 6**). This method can support decision-makers in designing and communicating policies that balance conflictive objectives.

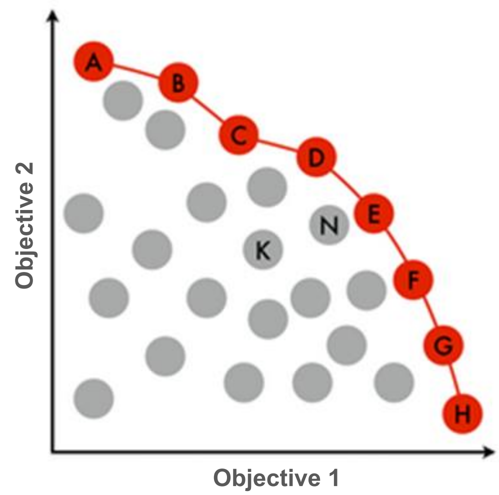


Figure 6. Exemplification of the Pareto Front Solutions
Note. The solutions highlighted in red are considered non-dominated, or Pareto set, because there are no solutions with a higher score on both objectives. In contrast solutions in grey are dominated, such as the N where E has a better performance in both objectives.

Some MOO methods rely on Multi-Objective Evolutionary Optimization Algorithms (MOEAs). There are many types of MOEAs but the algorithm ε-NSGAII has shown high performance compared to other MOEAs (Kollat & Reed, 2006) and has been widely used for similar projects (Trindade et al., 2017; Zatarain Salazar et al., 2022; Zeff et al., 2016). To tackle decision-making problems using MOO methods, it is necessary to formulate the optimization problem to identify the relevant objectives. Then, it is important to define how certain objectives will be incorporated in the optimization. Finally, one must determine how the desired solutions are going to be selected from the resulting Pareto Set.

2.3.1 Participatory Problem Formulation

As mentioned by (Afsar et al., 2023), exploring how to define objectives and constraints, also known as problem formulation or structuring, has benefited from less scientific attention than other aspects of MOO projects. Although every optimization-related project involves a problem formulation stage, many relied on “desk” analysis (as opposed to a participatory analysis) for problem structuring including in projects related to justice (Nyahora et al., 2020; Ramani et al., 2023). However, as this project focuses on justice interpretations for a real case, a participatory approach was chosen to structure the problem. Indeed, stakeholder involvement has been pointed out as a necessary tool for justice-related MOO problems (David Schlosberg, 2007; Valipour & Ketabchi, 2023). There are two types of stakeholder involvement in problem formulation for optimization problems:

- **Consultation** processes are those where data is gathered individually from individuals or groups that is then processed by analysts to identify trends and conflicting ideas. Consulting stakeholders is commonly used in formulation stages however it is rarely reported on and undergone under clear systematic methods (Afsar et al., (2023)). however, Afsar et al., (2023) have proposed a systematic approach to problem structuring and validation through interviews with domain experts.
- **Collaborative** processes are those where a group of individuals is tasked and guided to listen to each other and co-produce ideas that can be used for problem formulation. In his famous participation ladder, Arnstein (1969) places co-creation processes with a higher degree of participation than consultation as it can lead to more comprehensive and transformative solutions than consultation-based processes. Although only a few examples have been found of MOEA formulations using participatory workshops[2], participatory processes for DMDU are somewhat common (Bryant & Lempert, 2010; Popper, 2019; Popper et al., 2019). Additionally, Gold et al. (2023) proposes an Interactive Policy Exploration process to enable policy-makers to explore different framings and examine their implications. Although this participatory process is not proposed as part of the initial problem formulation stage, these authors, do recognize that this participatory process could influence the final problem formulation by providing feedback.

2.3.2 A-priori and A-posteriori Approach

The justice objectives in a MOO can be incorporated in different stages of the optimization. The objectives that are set as part of the optimization are referred to as a-priori. However, after an optimization has been made, additional objectives can be considered by filtering the policies in the Pareto set. This approach is referred to as a-posteriori. Shavazipour et al., (2021) applied robustness objectives as a filtering criteria for the Pareto Set to find policies that perform well across multiple scenarios. Znabei et al., (2023) performed a comparative analysis of these two approaches for an MOO project with Distributive Justice Principles. In this comparative analysis, the authors found that an a-priori approach can often provide better-performing solutions than an a-posteriori. However, the difference between the two can be marginal for certain objectives. Moreover, a-posteriori approaches, by having fewer objectives to optimize for, can provide faster optimizations and enable a quicker exploration of objectives. Thus, an a-posteriori approach provides more interactive decision support. Therefore, a-posteriori approaches have significant

---

[2] Literature review conducted using the Web of Science query ALL=((multi-objective optimization) OR (many objective optimization) OR (multi objective optimization)) AND AB=(particip* workshop)

advantages for decision-making, compared to a-priori ones for certain cases. It is unsure, however if these results can be generalized for other models. Thus, in this project, further experimentation was conducted to compare these two approaches and select the most appropriate for this application.

2.3.3 The Best and Compromise Policies

In MOO projects, oftentimes the policies that perform best for each single objective are highlighted (Nyahora et al., 2020; Shavazipour et al., 2021; Zatarain Salazar et al., 2022). If the optimization was conducted effectively, these best-performing policies should represent the ones that can generate the highest possible value for that specific objective, also known as global maxima. If the optimization is deficient, for example by stopping before converging, it will provide local maxima that could misguide policymaking.

Compromise policies are the ones that balance the trade-offs between objectives and perform best for a combination of objectives. As such, these compromise policies are often also presented as a highly relevant result of a MOO. They are often defined mathematically as the policies closest to the midpoint between normalized objectives (Rimon, 2023; Znabei, 2023).

2.4 Knowledge Co-production and Learning for DMDU

In complex, uncertain, multi-actor decision-making problems, it is necessary to integrate different worldviews (e. g., people's cultural values, preferences) and diverse knowledge and policy experience (e.g., decision-maker's conflicting objectives, power relationships) (Moallemi et al., 2023). The process of linking diverse values that people want to advance with the knowledge required to do so is referred to as co-production (Norström et al., 2020). By engaging stakeholders in collaborative problem framing, co-production of knowledge, and joint dissemination of solutions, the decision-making process becomes more comprehensive and with a higher chance of avoiding being short-sighted. This participatory approach ensures that the developed solutions are more legitimate, applicable, and resilient to the complexities and uncertainties inherent in socio-ecological systems, ultimately leading to better-informed and more widely accepted outcomes. Thus, participation and knowledge co-creation are crucial for addressing real-world problems characterized by value-related deep uncertainty.

Moallemi et al. (2023) conducted a literature review of DMDU experiences involving knowledge co-creation and developed a taxonomy of its incorporation based on nine characteristics clustered in three groups (**Table 2**). They identified at least 50 relevant DMDU projects involving knowledge co-creation and participation. Indeed, there's a growing interest on how to better implement participation in all stages of DMDU projects, from framing to implementation and monitoring (Moallemi et al., 2020) and for the variety of DMDU methods (Moallemi et al., 2023).

Table 2. Features of knowledge co-creation for DMDU projects
Note. Sourced from Moallemi et al. (2023)

Co-creation features		Description
Motivation	**Framing**	All the elements needed to define the model/problem (problem framing, decision scoping, stage setting, priority setting)
	Solving	All the elements needed once the problem is framed and solutions need to be identified (scenario assessment, solution evaluation, problem analysis)
	Acting	All the elements needed once a solution is selected (communication, planning execution, monitoring and evaluation)
Setting	**Actor**	Who is engaged in the process (what relation to the problem, level of power, etc)
	Timing	When are the stakeholders engaged (at what stage and with what frequency)
	Interaction	What type of participation is being held (consultation, knowledge exchange, horizontal interaction)
Impact	**Power**	Relationships between actors (ability to create or resist change, influence over others, conflicts and cooperation)
	Politics	What influence in the governance of the problem the actors have
	Change	As the guidance of transformation on the ground.

MOO methods are often used in tackling problems where different values and world views converge as they allow for the simultaneous consideration of multiple, often conflicting objectives. Several authors have reported their experiences in implementing participatory processes in MOO projects. For instance, the ParFAIT (Participatory Framework for Assessment and Improvement of Tools) method, as discussed by Smith et al. (2019), involves structured workshops to engage stakeholders in the evaluation and improvement of MOO tools for water resource management.

These workshops help utility managers to better understand the trade-offs involved and provide feedback on the usability of the tools, thereby enhancing the practical relevance of the optimization outcomes. Similarly, Bakhshipour et al. (2021) utilized participatory MOO approaches to design sustainable urban drainage systems, integrating stakeholder preferences into the optimization process to ensure that the solutions are both technically robust and socially acceptable

However, the literature, as highlighted by Afsar et al. (2023), indicates that MOO projects frequently neglect the crucial problem-formulation stage, assuming that the problem has already been correctly defined. In this stage of problem-formulation, knowledge cocreation can be crucial for avoiding suboptimal outcomes and a waste of resources. Afsar et al. emphasise the necessity of a systematic approach to problem structuring that includes the elicitation of expert knowledge and stakeholder engagement to identify and validate the decision variables, objective functions, and constraints before the optimisation process begins. However, they propose a method with the lowest form of participatory interaction, that is consultation via interviews, thus creating an opportunity to further formalize guidance for stakeholder involvement with more horizontal interaction. By incorporating participatory processes, such as workshops, into the problem-formulation stage, stakeholders can contribute to defining and refining the optimisation model, ensuring that it accurately reflects the complexities and priorities of the real-world context.

3. Research Design

A three-stage research process was designed to develop the Decision Support Tool for distribution policies of Guadalajara's Aquapheric (**Figure 7**). This design is a simplification of the DU_{ERAS} Pathway methodology from Gold et al. (2023) described in Section 2.

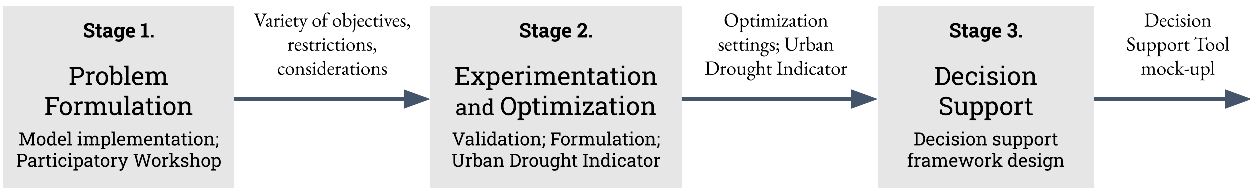


Figure 7. Project research design overview

The objective of the Participatory Problem Formulation stage is to define a model and a variety of optimization formulations that could later be used for the Experimentation and Decision Support stages. The first step was to adapt the existing water supply model developed by R-Cities (2022) to a Python MOO framework. This model's implementation follows the XLRM framework (Lempert et al., 2003) shown in **Figure 8**. After conducting initial explorations using the GDL model, a participatory workshop was designed to identify interpretations of justice and other insights useful for the following two stages. In particular, this workshop was designed to provide a variety of objectives, restrictions, and considerations that were later used to conduct experiments and guide the decision support proposal.

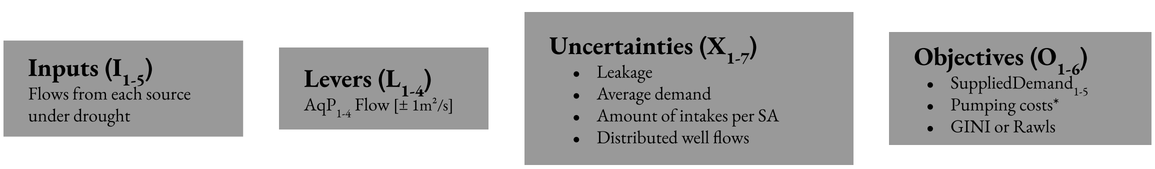
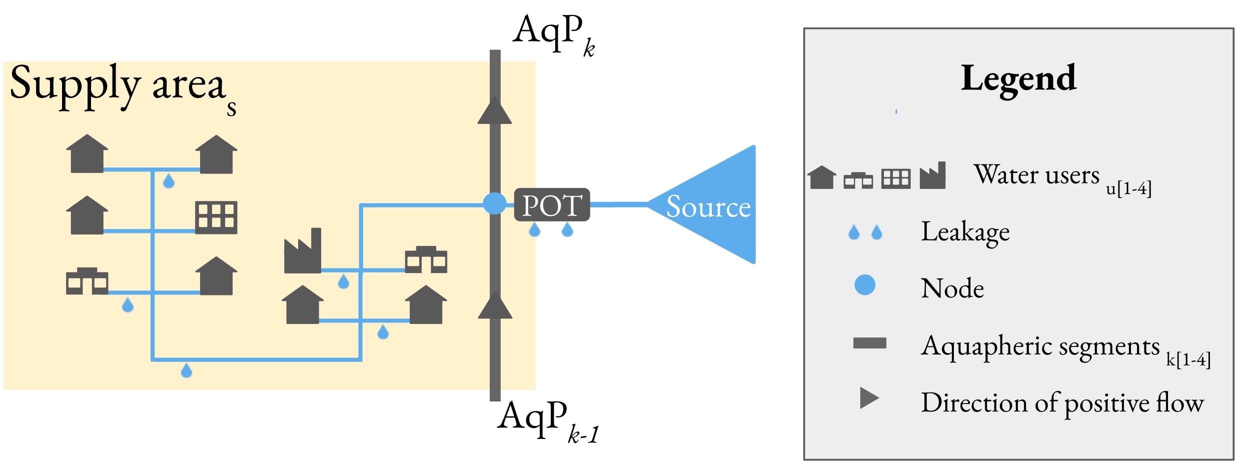


Figure 8. XLRM framework for the optimization GDL Model

The insights from the participatory workshop were then used to perform computational experiments aiming at designing an optimization formulation capable of reliably providing optimal policies for the variety of objectives proposed in the workshop. This optimization is powered by a Multi-Objective Evolutionary Algorithm (MOEA). These experiments are designed to explore the solution and drought conditions space. The insights from both stages 1 and 2 were then used to propose a final Decision Support Tool that is presented in the Results and Discussion Chapters.

3.1 Model and Data Sources

The project was based on the GDL Model developed by R-Cities together with the Government of Guadalajara in an eight-month-long collaborative modelling process (R-Cities, 2022). It is designed to compare the amount of water supplied to users and the amount of water demanded by users for each one of the five SA under different supply, demand and infrastructure scenarios. This model is available in an interactive decision-support tool[3] and built with data gathered from local authorities, processed and published by R-Cities (2022) and is summarized in Appendix 2. The GDL model was simplified for this study by removing alternative water sources such as rainfall harvesting and water reuse and adapted to Python. In this study, no validation procedure of the GDL model was conducted as it was validated by R-Cities and the local Government before its publication in 2022. All these datasets and methods carry out uncertainties that are further described in Appendix 2 and discussed in the limitations.



$$\underset{[m^3/s]}{\textbf{Demand}_s} = \text{intakes}_{s,u} * \text{average demand}_u \qquad \underset{[m^3/s]}{\textbf{Supply}_s} = (\text{source} * (1 - \text{loss}_{POT}) + AqP_{k-1} - AqP_k) * (1 - \text{loss}_{GRID})$$

Figure 5. Supply and demand description in the GDL Model

The water flow demanded by users is calculated by multiplying the amount of intake of each water-use in each SA by the average daily consumption by intake of each use. The average consumption for the four water users for 2020 is: domestic 128 l/day/person, services 558 l/day/intake, public 6272 l/day/intake (including all public buildings such as hospitals, schools, etc) and industrial 4457 l/day/person. Although domestic users have the lowest demand per-user they represent the highest consumers of water with 83% of the total water demand in 2020 (**Figure 9**). There's a small variation in the distribution of the water demand amongst the users of each SA. As the current implementation of the GDL model assumes constant average consumption per use for all SAs, this variation is only due to differences in the amount of intakes per use. The SA1 – PP1 has the highest demand of non-domestic users. This could be due to the presence of the city-centre and some of the most active industrial areas in this SA.

---

[3] https://public.tableau.com/app/profile/resiliencia.h.drica.amg/viz/HerramientadeResilienciaHdrica-AMGV12_4/Landing

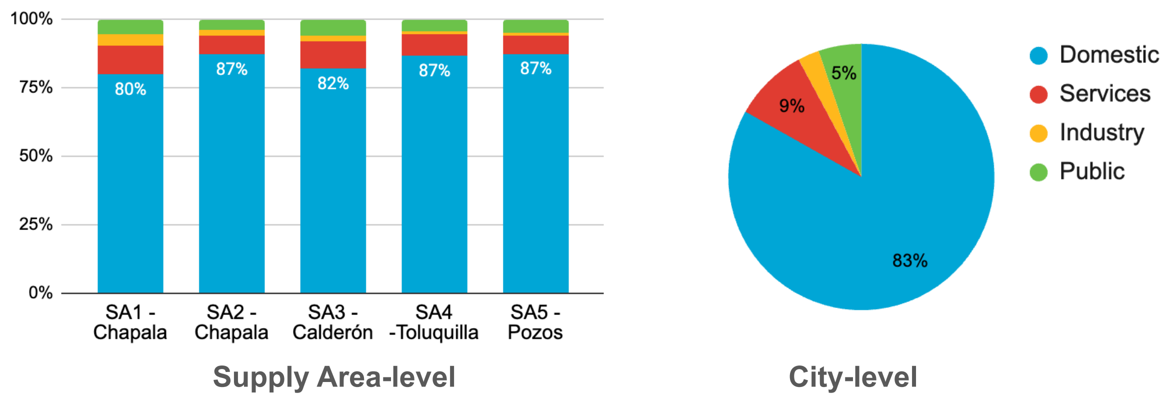


Figure 9. Water demand per use
Source: R-Cities (2022) with data of SIAPA 2020

The flow of water supplied to users depends on the water extracted from the sources minus the water leakages and additional inflows and outflows that happen in between the SAs. The model considers an average of 7% of water losses in potabilization and transport, that is all the losses that happen before water enters the distribution grid of the SA. The water supplied to the SA5 – Pozos does not consider this type of loss as it does not go through a potabilization plant.

After the potabilization plant, the water can be injected to the grid or can enter the AqP. Other water flows can reach or leave the SA in this stage. Using a small aqueduct, 12% of PP1's outflow flows towards SA4 – Toluquilla. This value was estimated by R-Cities (2022) using average values between 2012 and 2021 and was considered constant and not a lever. Additionally, in every SA there's decentralized wells that inject water to the system. There's high uncertainty about these flows. Thus they were estimated via a numerical calibration to balance supply and demand in all SA resulting in 20% of the extraction from the source Pozos destined to PP3 – Calderón and 2% destined to Toluquilla. These additional subterranean flows were also not considered as decision variables as they are highly uncertain and would rather be part of an extraction policy.

After the water has been potabilised and all the additional flows accounted for, the AqP flows can be then added or subtracted. As per convention, a positive flow is associated with a counterclockwise flow. An optimization restriction ensures that the AqP doesn't pump out more water than is available in the SA. The resulting flow is then distributed in the SA loses 35% of the water to leakage and other types of unaccounted water. The amount of water losses in the grid is highly sensitive to the age of the infrastructure and other aspects of urbanization but due to a lack of data, the leakage was considered homogeneous for all five SAs.

These uncertainties could have a considerable impact on how water is being distributed and if the distribution policy is able to attain its objectives. Thus, the code was conceptualized to easily incorporate new, more precise data in the future without affecting its core features. Additionally, these uncertainties were also considered in the decision to build a decision support system that favours flexibility and learning rather than robustness, as described in Section 4.4.

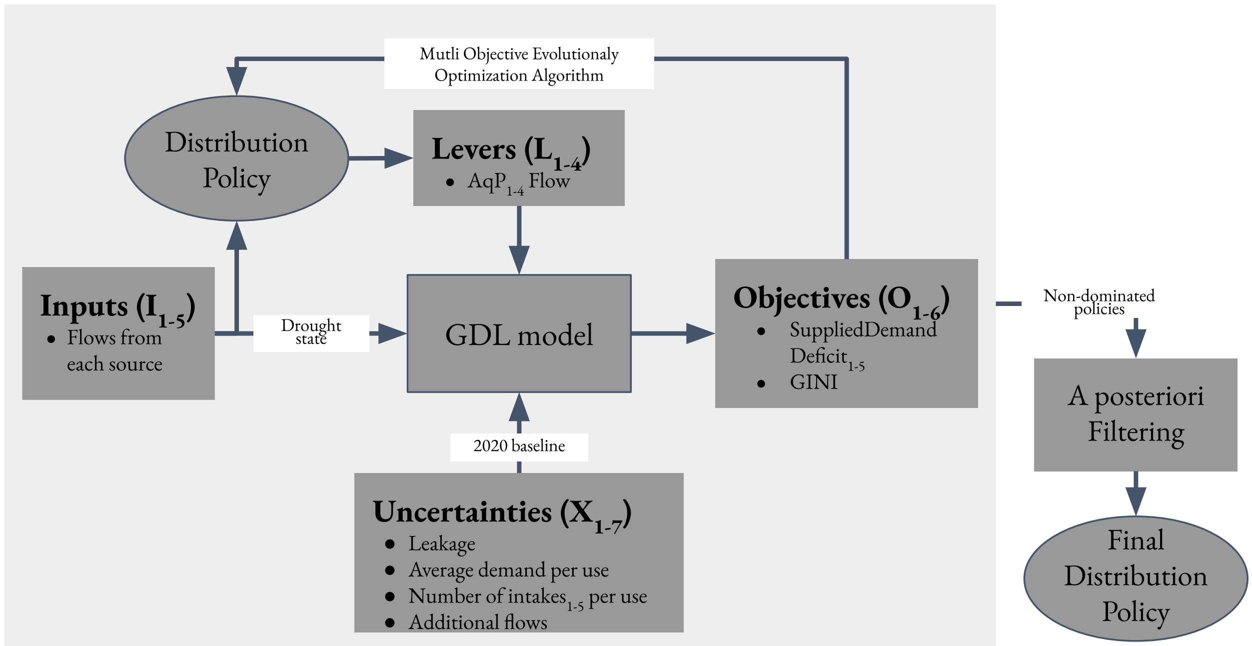


Figure 10. Summary of the simulation-optimization framework for the baseline problem formulation

The overall simulation and optimization framework that will be further described in the next sections can be summarized in **Figure 10**. This problem formulation, where there's a supply demand deficit objective for each SA and a GINI objective to reflect an Egalitarian principle was selected as the baseline problem formulation for the initial experimentation stages (Section 3.3) based on similar research (Rimon, 2023; Sarva et al., 2021).

This model was favoured over more complex formulations, for example by including delays and accumulations, as it enables more comprehensive experimentation. Additionally, simpler models can lead to higher trust and acceptability as they can be explained to stakeholders with any level of expertise. This approach aligns with the ideas of Helgeson et al. (2021) who argue that simpler computer models are epistemically better for informing decisions.

All the data from this model is described in detail in Appendix 2. The XLRM framework is further described below.

3.1.1 Levers

There are many means to manage drought in Guadalajara, such as managing demand, changing extraction patterns, bringing additional water flows, among others. However, this research focuses exclusively on how water can be distributed using the AqP during drought. Thus, the only levers considered in this model formulation are the flows of the four segments of the AqP. Each segment can pump 1 m^3/s of water in both directions independently. However, no water can flow between SA5 – Pozos and SA4 – Toluquilla due to insufficient pumping power to overcome the head difference. This current physical limitation of the system was mentioned in the workshop and was previously unknown to the authors of the research while conducting the early experiments. Although this formulation focuses only on the AqP flows, this formulation enables the consideration of interactions with other drought management policies, for example, if an extraction policy is implemented the input flows would change and thus the distribution policy would change accordingly. However, these additional levers for drought management are not optimized for.

3.1.2 Uncertainties

There are many uncertainties in how the system behaves and how the AMG model represents that behaviour. On the demand side, the total amount of intakes for the city is known, however, the data used is from 2020. Additionally, this data it is currently reported in a spatial unit called Patronato (similar to neighbourhoods), thus R-Cities conducted an approximation to assess water intakes on an SA-level that carries out uncertainties. Average demand by use was estimated with 2020 data for the whole city. This approach that assumes that all SA have the same per capita consumption also carries out uncertainties but there's currently insufficient data to do a SA level assessment. However, the model can accommodate future data to increase precision.

On the supply side, the main uncertainties are the water losses in the distribution grid. R-Cities estimated losses of 35% on average for GDL, but other studies present different values. This value was also calculated as a city-wide average but could be further refined to the SA level in the future as the areas have an infrastructure with different characteristics and might have different leakage ratios. Loss in potabilization is easier to measure as it is calculated as the difference between the input and output of the potabilization plants. However, this value varies as the quality of the inflow might affect the amount of water that needs to be drained as part of the potabilization process. These uncertainties are concentrated in a source csv file that could easily be updated as more data becomes available.

3.1.4 Relations

The AMG model developed by R-Cities in collaboration with the GDL Government uses the Simple Equations 1 and 2:

$$Demand_s = Intakes_{s,u} * Average\ Demand_u \quad \text{Eq. 1}$$

$$Supply\ to\ users_s = Source * (1 - loss_{POT}) + AqP_{k-1} - AqP_k) * (1 - loss_{GRID}) \quad \text{Eq. 2}$$

Where:

- **Loss**$_{POT}$ refers to the water losses in potabilization plants
- **Loss**$_{GRID}$ refers to the water losses in each SA's distribution network
- **s** represents the five supply areas
- **u** represents the four water uses (domestic, services, industrial and public)
- **k** represents one of the four AqP segments

By considering accumulations in the city's water tanks, these relations could be converted into differential equations to incorporate time. However, no data on tanks was available and little added value to such a model could be found compared to how complexity would have increased and explainability decreased. Thus, this simple formulation of the GDL model was considered fit-for-purpose.

3.1.3 Outcomes

Using the GDL model, any metric that involves the supplied flow and demanded flow can be calculated. These metrics can be at SA-level, also referred as performance indicators, or City-level, referred as aggregated metrics. The set of indicators shown in Table 3 was favoured over more complex indicators as they don't incorporate constants that reflect assumptions (e.g. the Prioritarian operationalization by Adler et al. (2017) that include ϒ and c_{zero} which represent moral choices of minima and priority to the worst of).

Afsar et al. (2023) distinguishes between outcomes for MOO projects that are monitored in real-time, outcomes based on data analysis and modelled outcomes. In the current stage of this project, only modelled outcomes were considered. However, the water authority mentioned that there are ongoing efforts to implement real-time monitoring that could eventually be used for designing more precise distribution policies.

During the workshop, one table highlighted the importance of reducing energy consumption for the AqP under low drought conditions. The length of the segments is varied and so is the head differences between the nodes. Due to these hydraulic differences, a flow of for example 1 m^3/s consumes a different amount of energy depending on the segment and direction. However, no data was accessible that could accurately represent those differences. Thus, the simplest formulation of the energy consumption was implemented where an energy consumption of 0 is when the AqP is not used and an energy consumption of 1 is when 1 m^3/s is flowing in every segment in any direction. Future works could greatly increase the accuracy of this energy consumption metric.

Table 3. Model outcomes or performance indicators

Note. The subscripts **s** and **s'** represent the 5 SA. The subscript **k** represents the four segments of the AqP.

Aggregation	Outcome	Formulation	Preference	Details
SA-level	**Supply per capita** [l/day/person]	$\frac{Flow\ supplied\ to\ users_s}{population_s}$	**Maximizing**	As there are other uses it does not represent how much water each person has access to but is a relatable indicator of water distribution.
	Supplied demand deficit [%]	$1 - \frac{Flow\ supplied\ to\ users_s}{population_s}$	**Minimizing**	The absolute difference between the current value and the default value of 100% of the *Supplied Demand*.
	Flow deficit [m³/s]	$Flow\ supplied\ to\ users_s - Flow\ demanded\ by\ users$	**Minimizing**	Difference between flow demanded by users and flow supplied to users in m³/s.
City-level	**Average *Supplied Demand*** [%]	$\sum_{s=1}^{5} \frac{Supplied\ demand_s}{5}$	**Maximining**	**Utilitarian Principle** Arithmetic average of the *Supplied Demand*.
	Average Supply per capita [l/day/person]	$\sum_{s=1}^{5} \frac{Supply\ percapita_s}{5}$	**Maximizing**	**Utilitarian Principle** Arithmetic average of the Supply per capita
	Supplied demand GINI	$\frac{\sum_{s=1}^{5}\sum_{s'=1}^{5} \lvert Supplied\ Demand_s - Supplied\ Demand_{s'} \rvert}{2 * 5^2 * Supplied\ Demand_s}$	**Minimizing**	**Egalitarian Principle** GINI coefficient of supply-demand values of the SAs
	Supply per capita GINI	$\frac{\sum_{s=1}^{5}\sum_{s'=1}^{5} \lvert Supply\ per\ capita_s - Supply\ per\ capita_{s'} \rvert}{2 * 5^2 * Supply\ per\ capita_s}$	**Minimizing**	**Egalitarian Principle** GINI coefficient of the Supply per capita of the SAs
	SAs below threshold	$\sum_{s=1}^{5} \begin{cases} 1\ if\ Supply\ per\ capita_s < threshold \\ 0\ if\ Supply\ per\ capita_s \geq threshold \end{cases}$	**Minimizing**	**Sufficientarian Principle** Number of SAs below the 142, 100 and 50 l/day/person thresholds
	Energy consumption [%]	$\frac{\sum_{k=1}^{4} \lvert AqP\ flow_k \rvert}{4}$ Where k represents the AqP segment and 4 is the maximum energy consumption where all segments are being used at max capacity	**Minimizing**	Due to a lack of data from energy consumption this simple implementation was used where energy consumption is a ratio of the maximum possible combined flow.

3.2 Participatory Problem Formulation

As detailed in Section 2.3.1, literature on MOO often pays little attention to how the optimization problems are formulated. Additionally, stakeholder involvement and co-creation for problem formulation is often overlooked but can be particularly meaningful in problems with highly contested value settings, such as those including justice considerations. A large proportion of the resources invested in this research project were destined to the design, implementation and analysis of a participatory workshop conducted in Guadalajara meant to provide insights for the formulation of the problem.

The workshop was conducted on April 12, 2024 with the title "*How to distribute water fairly when there's not enough: towards distribution policies for Guadalajara's Aquapheric with a justice and deep-uncertainty approach*". The event took place in the Campus of Guadalajara from El Tec de Monterrey.

Following Norström et al. (2020) principles for knowledge co-creation the workshop design considered: **context-based**, by giving a presentation of the decision-making problem and including participants familiar with it; **pluralistic** by valuing and navigating the empirical, technical and scientific approach to tackling the problem; **goal-oriented** by clearly defining the objectives of the workshop (Section 3.3.1) and **interactive** by fostering active engagement in the activities, arranging non-sectoral tables and allowing sufficient time for cross table presentations.

Three additional principles were considered for designing this specific participatory problem formulation workshop considering the complexity of this decision-making problem, which incorporates all types of deep uncertainty and that it has a high degree of novelty both on the challenges and methods:

- **Non-prescriptive**
  Participatory workshop design has to navigate the spectrum of how much freedom it offers the participants to propose ideas and structures. A very prescriptive workshop is one where the organizers have very specific questions and a defined set of answers and thus its results can be very readily analysed and documented. In participatory processes on the other side of the spectrum, participants have the freedom to propose ideas in any form and structure providing solutions potentially overlooked by the authors but at the expense of having results that can be more difficult to incorporate into the problem.

  The discussion within Guadalajara's decision-making arenas about how to deal with water distribution during drought is still in the early stages (A. Ayo, personal communication, November 13, 2022). Indeed, urban water scarcity is often considered as a failure of the system, thus the main focus lays on how to avoid the next failure rather than on how to manage it. Moreover, there are still few documented experiences about justice frameworks for this type of urban water distribution problems. Considering these relative early stages of the overall and specific problem framing, the workshop was intended to leave as much room as possible for participants to propose ideas while maintaining a certain structure. In practice, this meant that within the workshop participants were offered resources that they could use to frame their discussions and proposals, but they were constantly encouraged to propose new ideas.

- **Non-convergent**
  As the workshop was conducted in the frame of a thesis project with limited time and limited resources it was not expected to provide a single final answer to how justice should be interpreted for distribution of water in Guadalajara. Indeed, although the participants objectives in terms of amount, diversity, and degree of influence in the system were met as presented in Section 4.1, more workshops with more participants, notably with more societal representation, would be required to be able to find a single solution with high legitimacy. This workshop, however, was designed to provide a variety of problem formulation options and ideas that could later be used for numerical exploration. The results from this numerical exploration could later be used in a second participatory process such as the Interactive Policy Exploration workshop proposed by Gold et al. (2023).

- **Structured**
  The overall objectives of the workshop followed the characterization of problem conceptualization proposed by Afsar et al. (2023). This included defining problem conceptualization as determining conceptual goals, formalized objectives, constraints, decision variables and indicators to quantify objectives as well as their characterization of objectives into analytical, simulated, and data driven. To frame the justice discussion, the Distributive Justice Principles and their operationalization developed by numerous authors as described in Section 2.2. Additionally, the workshop benefited from very detailed facilitation material and trained facilitators to make sure that it provided useful insights.

The workshop agenda, objective and expected outcomes, as well as the facilitation tools are summarized in **Figure 11** and detailed in the next sections to present how this participatory problem formulation was designed and conducted.

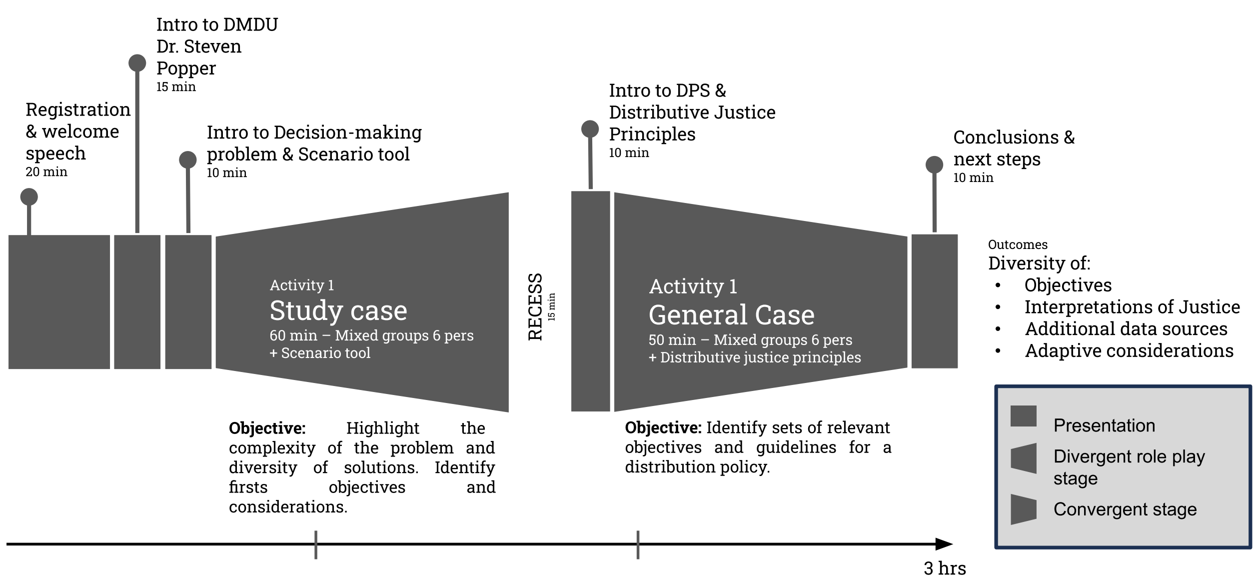


Figure 11. Workshop agenda, objectives and tools summary

3.3.1 Objectives

The main objectives of this workshop were related to provide insights for the problem formulation of the development of the distribution policies. These insights were thus framed in the following 5 of problem formulation in accordance with the framework proposed by Afsar et al. (2023):

- **Objectives**
  Defined as what the distribution of the AqP should strive to achieve. To frame these objectives, the Distributive Justice Principles using a predefined set of indicators was proposed. However, participants were encouraged to propose their own objectives structure with additional indicators if they felt they were necessary.

- **Indicators**
  Defined as what metrics should be used to define how water should be distributed. Indicators were divided into performance indicators, defined as the ones that describe how water is being distributed, and characterisation indicators of the SA that could be used to define how distributive justice should be operationalized. The real impact of a policy is highly determined by what indicators we use to design and evaluate such policy (Lepri et al., 2017), thus this part of problem formulation was paid particular attention to. The 3 performance indicators mainly discussed are shown in **Table 3**.

- **Restrictions**
  Defined as physical, political or social constraints on how water can be distributed using the AqP. Some of these restrictions were incorporated as optimization or model constraints or used in the overall discussion on decision support.

- **Considerations**
  Defined as elements that could influence the design or implementation of a distribution policy. For example, the importance of transparency on how the policies are designed is a relevant consideration mentioned that influenced the decision support proposal.

- **Interactions**
  Defined as relevant impacts from other policies that could affect how a distribution policy performs or how it should be designed. For example, participants mentioned a rainfall capture program that could reduce the need for municipal water supply in certain areas. This component is not mentioned by Afsa et al. (2020) but it was considered necessary as model boundaries were expected to become an important part of the discussion on the final policy advice.

- **Adaptive considerations**
  Following some discussions with one of the supervisors of the thesis, the idea that the objectives for this distribution policy could change based on the intensity of the drought emerged. This concept grounded both in Dynamic Adaptive Policy-making (Haasnoot et al., 2013) and in an intuitive approach to risk management such as the one described by Murphy & Gardoni (2008) was included in the workshop's design. Thus, part of the objectives of the workshop was to gather ideas for a possible adaptive distribution policy where the objectives vary in relation to drought intensity.

3.3.2 Participants and Location

The discussion on who to include in the participatory workshop was guided by research concerns and constrained by the available resources. The Tec de Monterrey team offered the Decision-Making Theatre as the venue. This recently built room is a high-technology environment specifically designed for events such as this workshop. It includes 5 large touchscreens and a 6x2m media wall. All of these screens can be centrally or independently controlled. The furniture can easily be set to varied spatial distributions but has a maximum seating capacity of 32 people.

Additionally, it was only possible to host one workshop during the thesis's timeframe. Considering these limitations, it was decided that the workshop would focus exclusively on representatives from government, academia and non-governmental organisations focused on water policy. This means that social representatives, particularly from vulnerable groups, would not take part in this workshop. In order to properly involve a broader range of societal groups, additional resources would have been required to conduct multiple large-scale workshops. Therefore, it was decided to frame this lack of representation as a limitation of the study rather than involving a couple of members of societal groups to avoid a tokenistic approach to participation and pretend that all sectors took part in the workshop. To tackle this limitation, a representative participation approach was selected by inviting individuals with experience and responsibilities towards vulnerable sectors of society, such as government officials and socially engaged researchers. Additionally, within the research design, particularly in the triggering questions described in the Agenda Section, it was ensured that discussions about the impacts and implications of a distribution policy towards vulnerable sectors of the population would be considered. Finally, documents were consulted that did conduct large participatory processes such as the City Water Resilience Agenda (R-Cities, 2022), the Climate Action Program (IMEPLAN, 2020).

3.3.3 Agenda

The workshop duration was 3 hrs as it was signalled by the organising committee to be the maximum time that stakeholders are willing to invest in such events. The agenda included one key presentation, three contextual presentations and two main participatory activities.

After a 20 min buffer time to account for late arrivals and the protocolary welcome speech by the University authorities, the workshop started with an introduction to DMDU by Dr. Steven Popper, one of the founders of the field and lead researchers from RAND and now working as Faculty of Excellence in El Tec de Monterrey. This presentation was designed to describe why DMDU was created, what methods are used and how it has been used in Mexico and the world. Additionally, Dr. Steven Popper introduced the concept of deep uncertainty and highlighted value uncertainty as a key challenge in many decision-making processes. This presentation, beyond introducing the methods, also increased the project's legitimacy and was highlighted by some participants as a highly valuable part of the workshop (Annex n).

Activity 1 – Study case

After introducing the decision-making problem, the tools and instructions for the first activity were presented **Figure 12**. The objective of the first activity was to effectively convey the complexity of the decision-making problem and start identifying some ideas towards a solution. To achieve this objective, instead of a presentation, the participants were asked to step into the shoes of a water manager and were tasked with dealing with a simulated drought condition by agreeing on how to use the AqP to distribute the available water. This sort of role play is a common facilitation technique that can uncover hidden layers of complexity (Rooney-Varga et al., 2018). For this activity, the participants had access to an **interactive Scenario Exploration Tool** (Section 3.3.4) that enabled them to explore how to solve a particular drought scenario and see the impacts of the AqP flows they selected. The chosen scenario for this activity was the drought of 2021 that motivated the construction of the AqP as it is a well-known situation by the participants and that R-Cities (2022) had published the water flows for that scenario. Additionally, they had access to characterization data that they could use to guide their proposals but were encouraged to use any information they wanted.

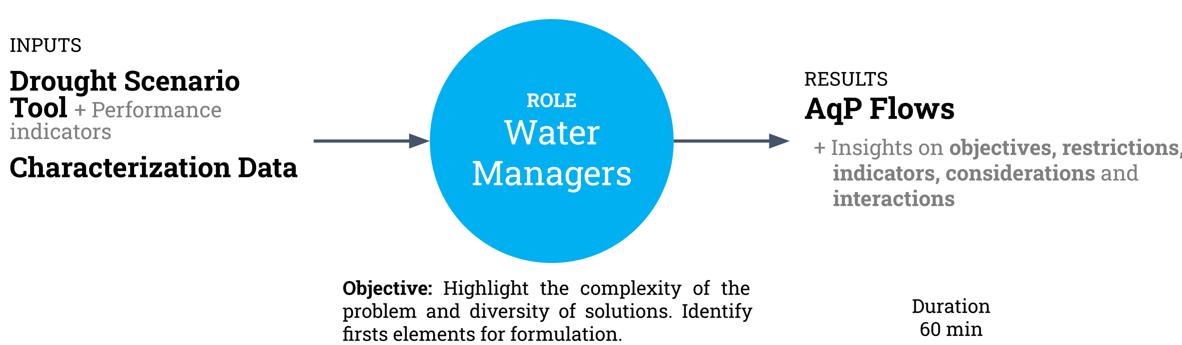


Figure 12. Summary of workshop Activity 1

Within the tool participants could visualize the water system and see all the information about the different elements of this system gathered by R-Cities (2022). This information layer would serve as a levelling ground to build a common understanding that could facilitate further discussion. The participants could interact with the system by selecting a drought scenario that would modify the flows of the water sources. They could also manually modify the flow values of the AqP segments. These interactions would affect the water supply conditions of the SAs which would change colours accordingly. The participants also could choose among one of the three performance indicators (**Table 3**) to measure what is the impact of the distribution policy they are exploring

While the participants were discussing what flows of water to set in each segment of the AqP to tackle the drought scenario, the facilitators started to take note on post-its of the ideas being mentioned about the objectives, indicators, considerations and restrictions for a distribution policy. These post-its were then placed on a large format facilitation sheet and could be used to further frame and catalyse the discussion. The participants were not directly asked to mention this information, as this MOO formulation framework and vocabulary had not been introduced. Rather the discussion was left open and unstructured, such as the one water managers might undergo if there is not yet a distribution policy established. However, starting to arrange the outcomes of Activity 1 under this optimization problem formulation framework was later going to be used as a leeway to Activity 2 and would be useful for the analysis of the workshop.

The facilitators also had access to trigger questions designed to unravel layers of complexity of the decision-making problem and highlight the nuances of potential solutions. Some of these trigger questions were derived from the literature on the Distributive Justice Principles, particularly the limitations of each principle gathered by Doorn (2019) and summarized in Section 2.2. For example, when a group was converging towards an Egalitarian solution, the facilitator could ask them how they would deal with the SAs that they are taking water from in order to increase the supply to other areas (this is called the levelling down objection . Other triggering questions resulted from the desk analysis of the decision-making problem and the first optimization experiments. These questions along with the rest of the materials available to the facilitators can be found in the Facilitator Guide in Appendix 3.

Activity 1 finished with a round of presentations where each table explained how they tackled the drought conditions and what was their decision-making process using their facilitation sheet. The facilitators made some final comments before starting a 15-minute coffee break.

Activity 2 – General Case

During the coffee break the facilitation team gathered to build a summary of the learnings of Activity 1. This summary was then presented to kick-start Activity 2. The main similarities and differences between the tables were highlighted using two charts that were previously coded to be built quickly in order to showcase the AqP flows proposed by the four tables as well as their effect on the SAs. These visuals were also used to introduce the characteristic parallel axis plots from MOO such as the ones that can be seen in **Figure 21** and **Figure 29**. Additionally, the facilitators summarized the comments mentioned by participants related to complexity of having a discussion about justice and of defining specific flow values for each segment according to such discussion.

After summarizing the complexity of the decision-making process using words and ideas mentioned by the participants, the methods of this research project were presented as one possible path to tackle these complexities. MOO was introduced as a proven and innovative method to find numerical solutions to complex problems with multiple and competing interests. Distributive Justice Principles were introduced as a way to frame and interpret justice that integrates the ethical discussion and the technical one with precise mathematical formulations and documented experiences from other projects. The visual and conceptual vocabulary that will be used in Activity 2 and for the overall research project was also introduced.

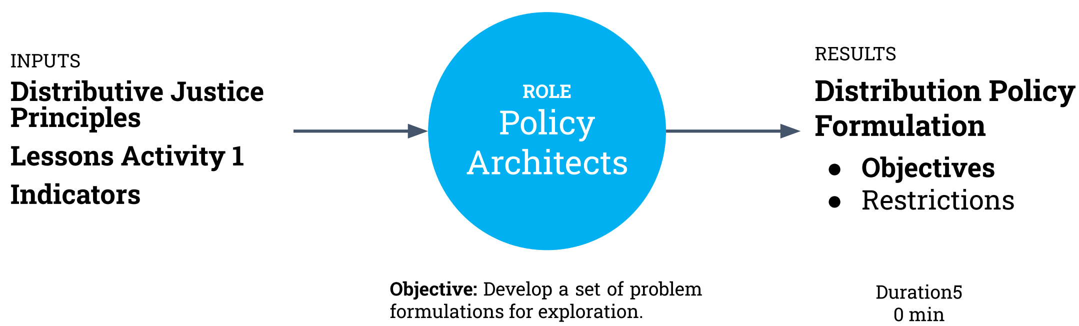


Figure 13. Workshop Activity 2 summary

For Activity 2, participants were asked to step into the shoes of policy architects who would design a general distribution policy for the AqP (**Figure 13**). A distribution policy was defined as a set of constraints the AqP has to comply and a set of objectives that it should strive for. In the initial design of the workshop, objectives had no defined structure. But after one of the workshop dry runs this approach was deemed too confusing. For the final design a set of four objectives structures were defined, one for each DJPs. These objectives were laid down in objective cards (**Figure 15**) that had a sentence with missing words and empty spaces that the participants could fill with stickers to define the operationalization of the objective. The stickers were colour-coded in accordance with the colours of the empty spaces in the objective cards to facilitate the formulation of objectives (**Table 4**). Additionally, blank stickers were distributed and empty space in the cards was left in order to accommodate for new proposals. Stickers with different drought conditions (high, mid and low drought) were distributed even if the idea of changing the policy objectives based on drought conditions was not mentioned in order to avoid a forced convergence towards this adaptive approach (Section 3.3.1).

Table 4. Stickers for the objective cards of workshop Activity 2
Note. These colours match the ones in the empty spaces in the Objective Cards (**Figure 15**)

Performance indicators	Vulnerability indicator	Drought conditions	Supply area(s)
Supply per capita [l/day/person]	Marginalization Index	**Low drought**	ZA1, 2, 3, 4 or 5
Supplied demand [%]	Water Vulnerability Index*	**Mid drought**	All ZAs
Flow deficit [m^3/s]		**High drought**	

While the participants started formalizing their objectives and problem formulations, the facilitators could ask trigger questions to help them consider as much as possible of the complexity of the problem. These trigger questions were designed based on the limitations of the DJP (Doorn, 2019; Znabei, 2023) and are included in the Facilitator Guide (Appendix 3).

After a round of presentations from the groups describing their problem formulations and final comments from the facilitators, a last presentation was made. The next steps in the research were introduced and a broader vision of Integral Water Scarcity Management (Section 5.5) was introduced to locate the project within a larger framework of resources to prepare for climate change effects in urban environments subject to drought.

3.3.4 Materials

To frame the conversations, keep participants engaged, effectively communicate the research concepts and ensure that the workshop would provide meaningful insights, the following printed and digital materials were developed.

Facilitation Sheet

A large format A0 facilitation sheet was printed and taped to each one of the four tables. This facilitation sheet would serve to guide the discussion and to showcase the collective knowledge that was being co-produced by each table (**Figure 16**). Post-its were provided for Activity 1 and the Objectives Cards (**Figure 15**) for Activity 2.

Supplementary material

A technical support sheet was provided with a more in-depth description of the GDL Model and the methods of the thesis to avoid making presentations that might get too technical and could steer the discussion away from the distribution policies (**Appendix 5**). Additionally, a characterization sheet (**Appendix 6**) was distributed that included relevant data about the SAs such as demographics and water consumption data produced by R-Cities (2022) and water-related vulnerability indicators published by Díaz-Vázquez et al. (2023). These materials were available to the participants during both Activities.

Boundary Object - Interactive Scenario Exploration Tool

Interactive tools to explore scenarios, discuss causal relations and perform rapid evaluations of proposals have been proven to successfully support decision-making processes involving complex multidisciplinary problems (Schwartz et al., 2018). Pairing these tools with role-play-style participatory activities can further enhance its potential (Rooney-Varga et al., 2018). In the workshop, a wide diversity of experts and decision-makers participated, with different levels of familiarity with the specific decision-making problem of the Aquapheric. An interactive tool was developed in order to facilitate the conversations between these participants (**Figure 14**). This tool had two main layers:

- **Information layer**
  This layer was designed to provide the user with precise knowledge about the system that could serve as a levelling ground to foster discussions. All the information was sourced from the City Water Resilience Agenda (R-Cities, 2022).
  - **Visual representation of the system**
    Using shapefiles from the base layer, main water bodies, supply lines, potabilization plants and supply areas, a map of the system could be built.
  - **Data on the elements of the system**
    Hovering on any of the main elements of the system displays a small paragraph with a description of the system and key values (see Appendix 3).
  - **Performance indicators**
    The only layer of simulated data, as opposed to sourced from the literature, are the values of the performance indicator for each SA calculated using the flows from the sources and the Aquapheric. These values are displayed in text and also in a choropleth from the SA. Users could choose among the three performance indicators from the AMG model (**Table 4).**

- **Interaction layer**
  The tool was powered by the GDL model described in Section 3.1. This model enabled the interaction with the system by modifying water flows in accordance to predefined scenarios and to modify the flows of the AqP as means to deal with each drought scenario. In both of these interaction modules, additional information was provided upon hovering to explain how the interaction takes place and what is the data and methods supporting it.
  - **Drought scenario**
    The drought scenario module enabled the selection between two scenarios derived from data from R-Cities (2022): 2021 Drought that represents the conditions of scarcity of 2021 when no flow could be extracted from the Calderón Dam and the other sources slightly over-exploited; an RCP8.5 synthetic drought produced by Meraz et al. (2022) an published by R-Cities (2022) that represents high drought conditions and could be used to explore more extreme scenarios.
  - **Aquapheric flows**
    The tool enabled users to select the flow of water in each segment of the AqP. By convention, anti-clockwise flow was defined as positive and clockwise was defined as negative.

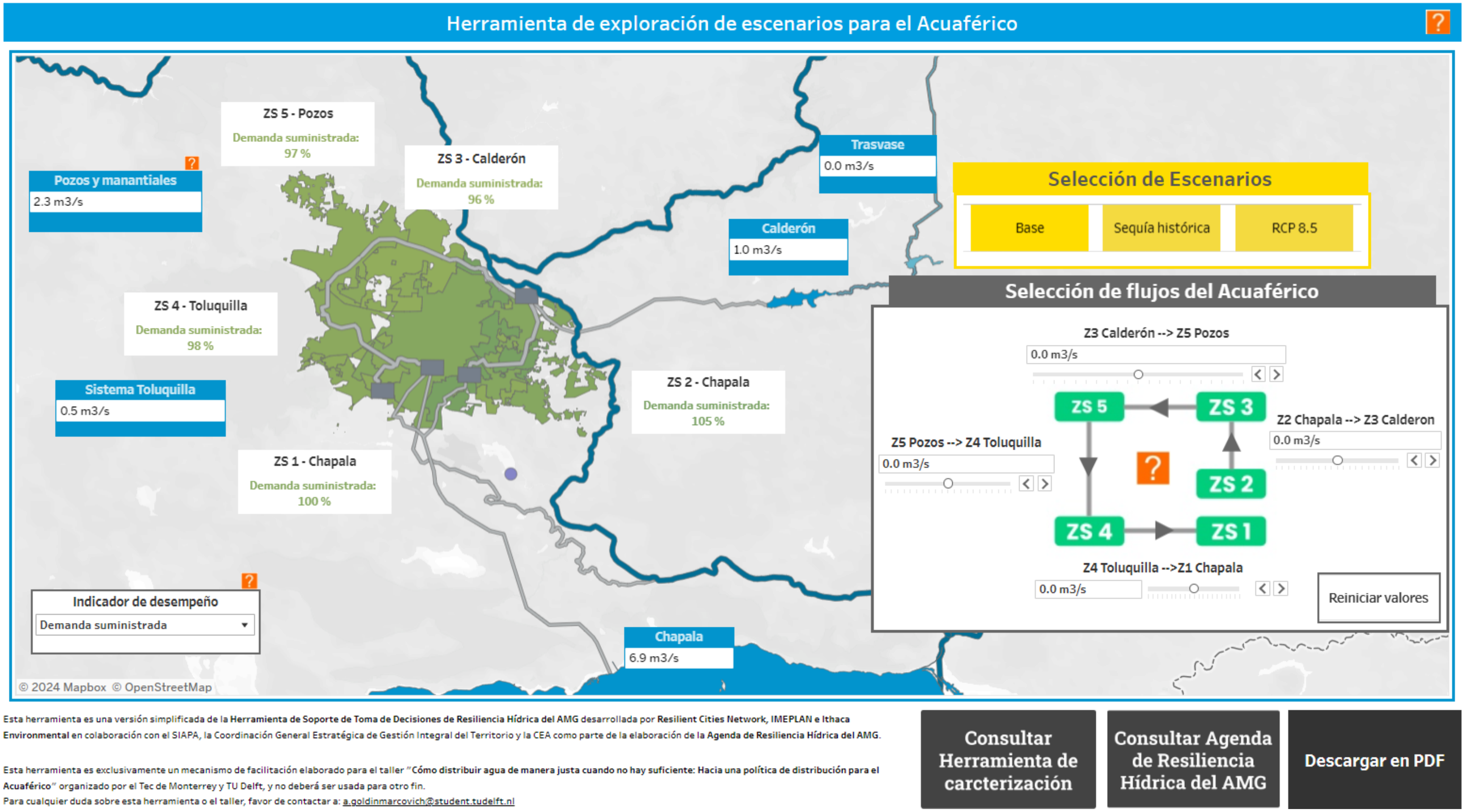


Figure 14. Snapshot of the Drought Scenario Exploration Tool Used in the workshop

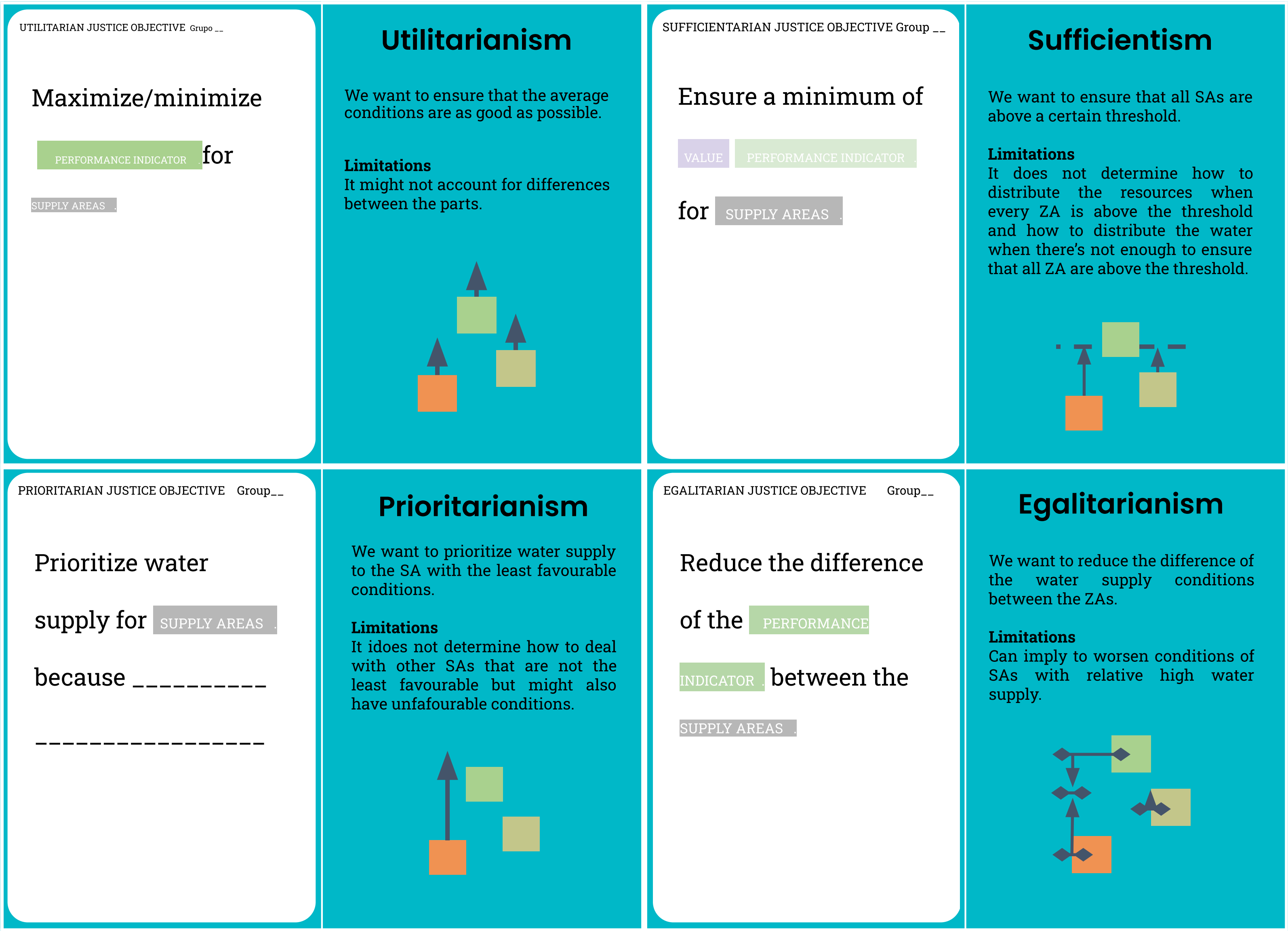


Figure 15. Objective cards used in the workshop.

Note. Each pair of figures is the front and backside of the cards. 3 additional cards were printed without a specified objective sentence, a generic justice objective card, an economic one and a generic objective card to enable unexpected objective proposals.

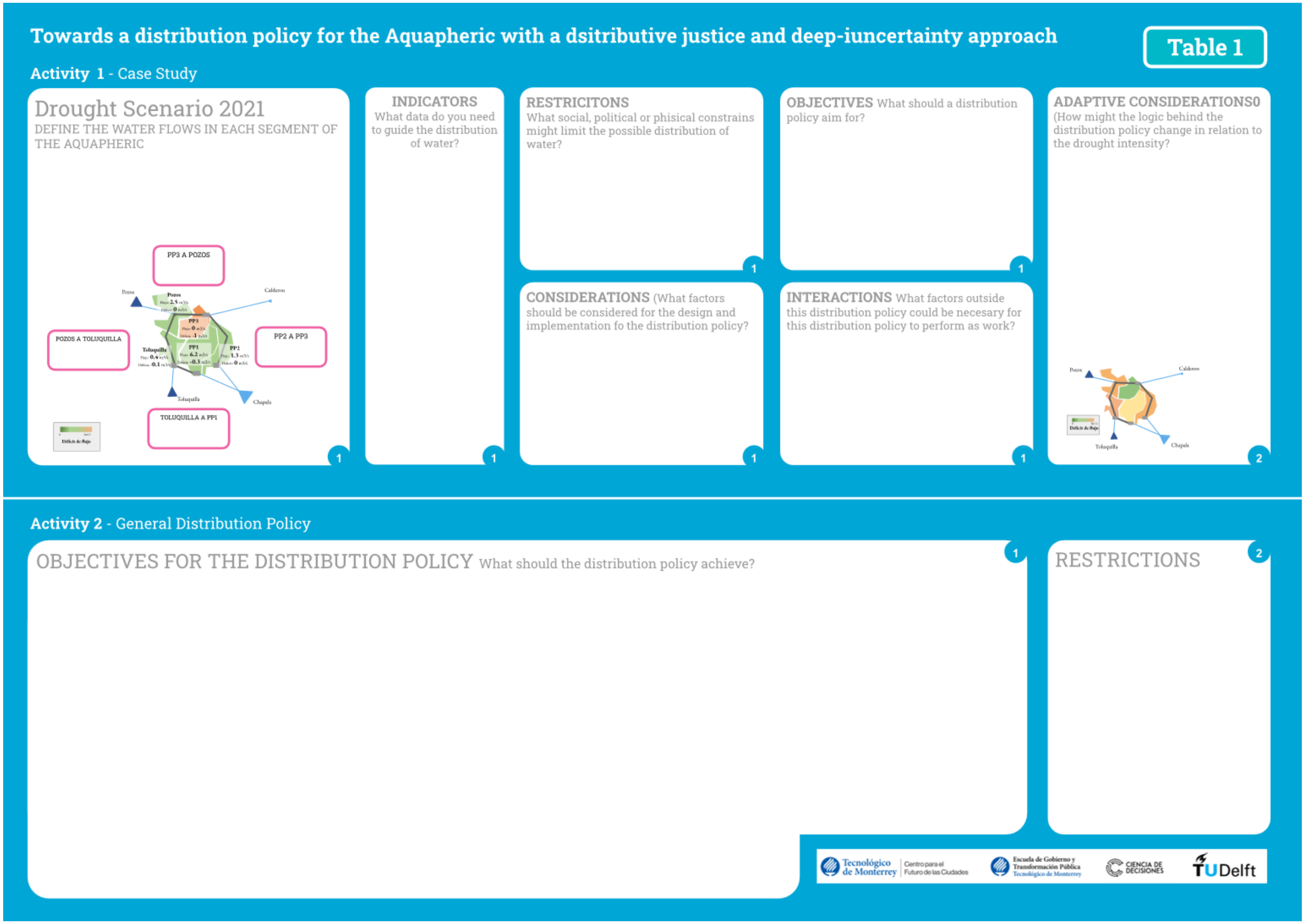
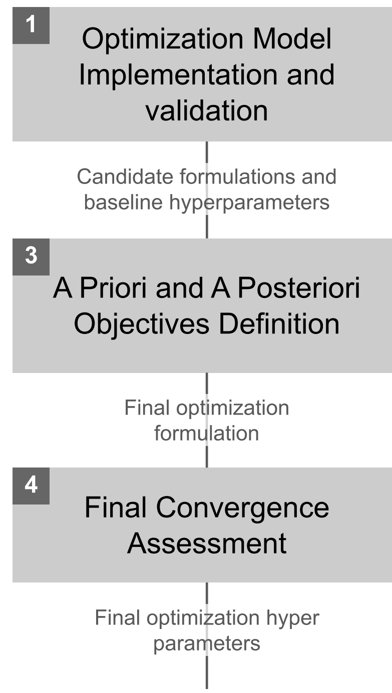


Figure 16. Workshop Large-format Facilitation Sheet

3.3 Experimentation and Optimization

This study doesn't aim at finding a single policy that would reflect how the city should interpret justice for water distribution under drought and that performs optimally for all possible drought conditions. This study, on the other hand, aims at developing a decision support tool that enables decision-makers and water operators to explore different policies that reflect a variety of justice interpretations and that are optimized for the current drought conditions. As such, the tool will be powered by an algorithm that conducts an optimization every time that a decision needs to be taken and then enables the selection of objectives as filtering criteria. This feature enables high flexibility and could offer better-performing policies than developing an adaptive policy that is trained on a wide range of drought conditions such as Direct Policy Search. However, under this approach, the optimizations will be run without the supervision of an analyst. Thus, there are risks of falling into optimization artefacts such as non-convergence, discontinuities and local Maximas. To mitigate these risks, a series of experiments were conducted to define the optimization settings that can ensure that no such artefacts can significantly affect the optimization results for any possible drought conditions and objective formulations while keeping run time low.



1. **Perform a simple validation of the Python model and optimization implementation**
   The model had already been validated by R-Cities and the Government of GDL before the publication of the Resilience Agenda. Thus, this stage focused only on ensuring that the Python code was working properly and that the optimization was properly implemented. To do so, an optimization with the baseline formulation was conducted for the 2021 Drought scenario, the same used in Activity 1 of the workshop. The results were compared with the empirical solution for the 3 tables that tried to find the most Egalitarian solution (**Figure 21**. Results from workshop Activity 1.

   For this validation procedure, a single objective optimization was conducted using Supplied Demand Deficit GINI. Supplied demand deficit was selected because previous experiences with MOO have shown that minimising objectives converge better than maximizing objectives. The MOEA used is ε-NSGAII embedded in the EMA-Workbench which has proven useful in other similar projects (Rimon, 2023; Znabei, 2023).

2. **Conduct an optimization for three characteristic optimization formulations for three characteristic drought scenarios**
   Optimal policies for different distributive justice objectives can be found by filtering the Pareto Set, even if those objectives are not included in the optimization formulation (Shavazipour et al., 2021; Znabei, 2023). This approach, called a-posteriori (Section 2.3), offers the benefit of enabling quick exploration of different objective combinations without

requiring to perform additional optimizations. However, it is important to ensure that the policies found with this a-posteriori approach are indeed optimal for the specified justice objectives.

To select a final problem formulation, an optimization was run for each candidate problem formulation and for the three representative scenarios. The best-performing policy for each objective was compared between the three candidate problem formulations for each representative scenario. Additionally, an assessment of compromise policies was also conducted. The candidate objective formulations are:

- **A-posteriori formulation** *(Supply Demand Deficit)*
  This represents a pure a-posteriori formulation where no justice-related objectives are included in the optimization. In this formulation, the algorithm tries to minimize the relative difference between the water demand and water supply for each SA. By having the least amount of objectives, this is the simplest and fastest optimization.

- **Mixed formulation** *(Supply Demand Deficit, Supply per capita GINI, Energy costs)*
  This formulation incorporates one justice-related objective and an economic objective. The most recurrent objective proposed in the workshop, the Egalitarian principle with *Supply per capita* was added as well as a simple objective for the cost of pumping water with the AqP to ensure that high-performing policies for these two objectives are found.

- **A-priori** (*Supply Demand Deficit, Energy and all justice objectives***)**
  This formulation includes all the objectives available in a fully a-priori approach. It is similar to the mixed formulation but also includes *Average Supply per capita* as a Utilitarian objective and *Supplied demand GINI.*

These formulations were used for three characteristic drought scenarios to make sure they performed as expected for the complete drought space. Many methods for identifying characteristic scenarios were tested, such as clustering based on drought intensity and doing natural breaks on the drought variables. However, these methods commonly used in scenario exploration generated artefacts. Thus, the selected approach was to generate scenarios based on observed and empirical scenarios that would represent three drought conditions sufficiently different, relatable and representative (**Table 5**):

- **2021 drought**
  This is the scenario that motivated the construction of the AqP where the Calderon Dam couldn't supply any water for over 4 months.

- **Chapala incident**
  Shortly after the workshop, the pumping system of the Chapala aqueduct broke allegedly due to instability in the electric grid (El Universal, 2024). The values of the flows during the days that the aqueduct was not operational were not published. Thus, to build this scenario the flows were estimated using the average flow of the Chapala Aqueduct subtracted from the flow extracted during the 2021 drought. The flows from the other four sources were assumed equal to the baseline conditions.

- **Groundwater scarcity**
  There has not yet been a report of a reduction in groundwater extraction, however, all the aquifers of the city are considered overexploited and the risk of groundwater scarcity has been extensively signalled (IMEPLAN, 2020, 2023; R-Cities, 2022). To account for this scenario for which there's not yet available data, an arbitrarily selected multiplier of 0.3 was applied to both subterranean sources. The other sources were set to the baseline flow conditions.

The average flows from the 4 water sources for each scenario are shown in **Table 5.** The flows for the 2021 drought scenario were sourced from R-Cities (2022). The other two scenarios were developed empirically to explore the uncertainty space with scenarios that are possible and could stress test the system in a sufficiently critical and particular way.

Table 5. Flows of the sources for characteristic scenarios

	Chapala	**Calderon la Red**	**Pozos well system**	**Toluquilla well system**
2021 drought	7.1	0	2.2	0.4
Chapala accident	1.8	1	2.2	0.4
Groundwater scarcity	6.9	1	0.69	0.15

3. **Conduct a final assessment of convergence for the three representative drought scenarios to define the final optimization hyperparameters for the final problem formulation**
   Once the final optimization is defined, an assessment of convergence for the three scenarios was conducted to ensure that the hyperparameters are sufficient to provide an accurate Pareto Front with sufficient resolution.

   Hypervolume was selected as the main convergence metric as it is considered "the most thorough convergence metric" (Zatarain Salazar et al., 2022). This metric assesses convergence and diversity by comparing the multi-dimensional volume of the Pareto set with a reference set.

3.4 Decision Support

A Decision Support Tool (DST) for Distribution Policies of the AqP was designed. This Tool integrates the insights from the literature and the Justice Exploration Workshop to support the process of developing and selecting distribution policies for the AqP. The design features of this DST (**Figure 17**) answer the uncertainties and limitations of the decision-making problem (Section 1.1).

This problem is characterized by value uncertainty regarding what should be the ethical principles for water distribution under drought. Thus, the formulation of the DST was made using a participatory and numerical exploration of justice interpretations rather than a prescriptive definition of the relevant justice principles based on literature. Additionally, as values evolve and there's a gap between the ideal distribution and the possible one due to limitations in the system, the DST offers decision-makers the possibility to choose and explore a set of different objectives rather than presenting a definitive, smaller set of preferred objectives.

As any complex system, the water supply system of GDL will continue to evolve and so will our understanding of it. The DST has to be able to incorporate new knowledge and the system's evolution as a mechanism to tackle system and future-related uncertainty. Thus, the code was built in such a way that if there's new data that characterizes the system with more precision it can easily be incorporated by updating a csv file. Additionally, as the future drought conditions in GDL are uncertain, the experiments were conducted for a space-filling design of the possible drought conditions rather than with a synthetic dataset based on historical data.

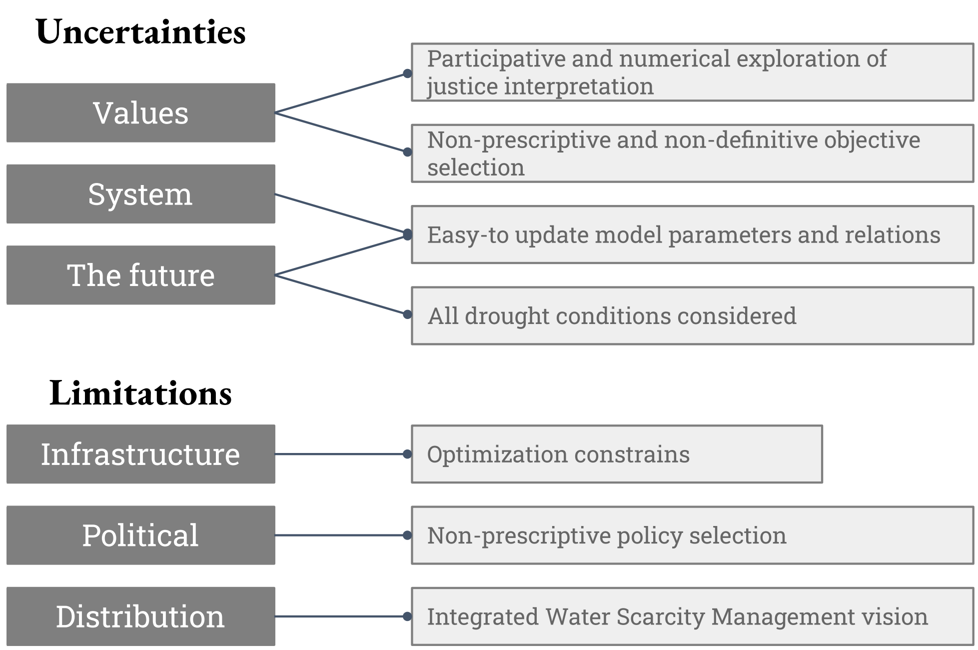


Figure 17. Design Features of the Decision Support Tool

The limitations of the infrastructure gathered from the literature and in the participatory workshop (Section 4.1.1) were incorporated into the DST as constraints in the optimization. These constraints, particularly the impossibility of pumping water between the SA5 – Pozos and the SA4 – Toluquilla, were implemented as a key-word argument to enable experimentation that could inform under what conditions this lack of pumping capacity reduces the city's resilience to drought and if additional pumping capacity is necessary.

Political constraints that might influence what distribution policy can be implemented such as contracts, agreements, promises, etc have been accounted for by offering a flexible DST that lets decision-makers select objectives and explore the solution space. This feature also implies a risk of a lack of transparency and accountability that should be dealt with by defining a Distribution Policy that determines what objectives should be used under what conditions. A future Policy Exploration workshop could be used to lay the foundations for such a Distribution Policy.

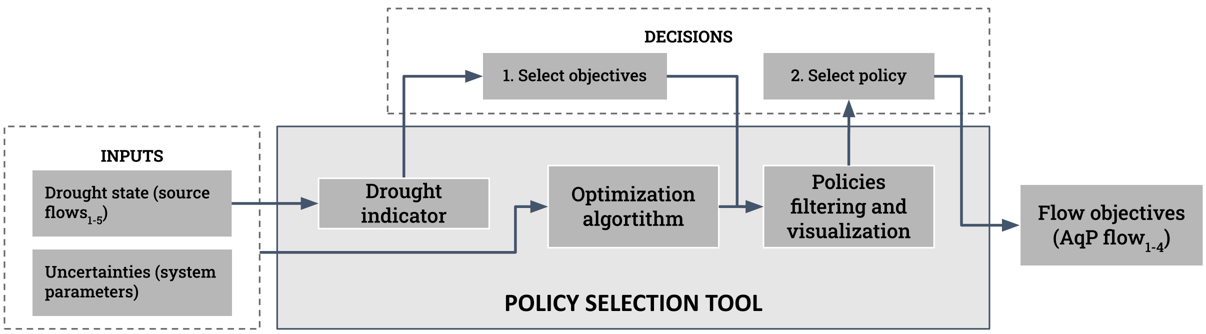


Figure 18. Conceptual Layout of the Decision Support Tool for distribution policies

Considering these design features the final concept for the DST for distribution policies for Guadalajara's Aquapheric is proposed as shown in **Figure 18**. This tool, when inputted the current drought conditions first calculates an Urban Drought Indicator. The decision-maker, informed by the current drought intensity can then select a combination of objectives. Based on such objectives, the policies on the Pareto Front can be filtered out to provide a set of best-performing policies for each objective proposed, as well as the compromise solution between them. The decision maker can the chose amongst these suggested policies to define the final flows for each segment of the AqP. This process could be conducted following the current weekly programming decision time frame. The system uncertainties, such as the number of intakes per SA or average consumption, can also be updated via a CSV file. This feature could be used to tackle the system uncertainties and evolution with limited effort.

4. Results

This section presents the findings from the three main sections of this Research Project.

4.1 Participatory Problem Formulation

The main activity conducted for the participatory formulation stage was the Justice Exploration workshop. As a result of a 3-month long planning process, 26 representatives of the local Government, Academia and International NGOs participated in the workshop (**Figure 19**). In particular, the Distribution Directors of both the State Water Commission (CEA in Spanish) and the local Water Utility (SIAPA) participated bringing highly valuable insights to the discussion and increasing the potential impact of this research and future related projects. High-level representatives of Academic institutions of El Tec de Monterrey (the host university) also participated including three deans and the director of the Centre of the Future of the Cities.

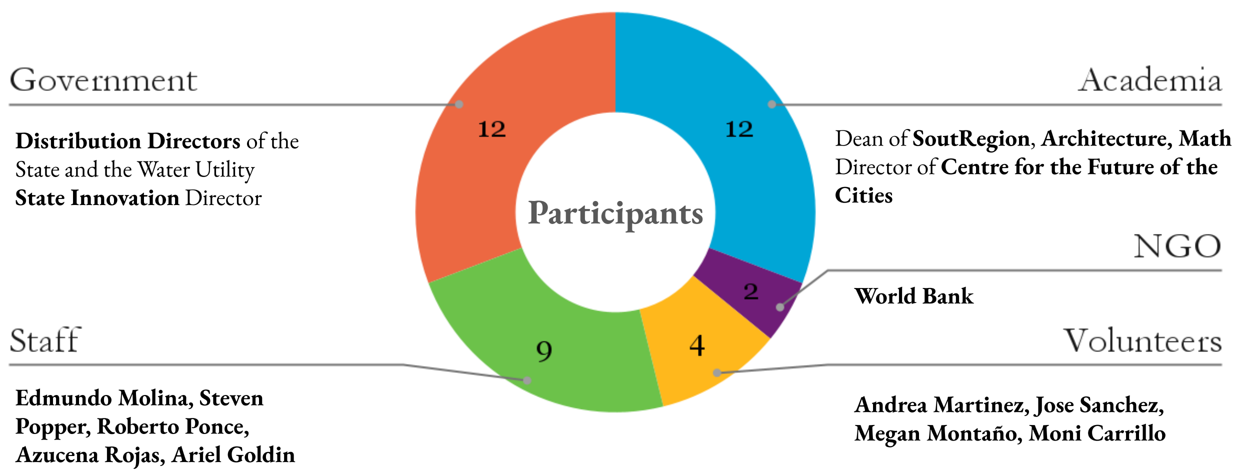


Figure 19. Summary of workshop Participants

This workshop was designed with both knowledge-sharing and knowledge co-creating objectives. Restrictions and other types of considerations that were necessary to refine the model or formulation of the optimizations were gathered from the participants more efficiently than if individual interviews had been pursued. Additionally, by making non-sectoral tables effective knowledge co-creation could take place to develop objectives and discuss indicator selection and applicability. After the workshop a feedback survey was sent that was used to discuss limitations and improvements of this stage (Appendix 6).

Figure 20. Workshop photos

4.1.1 Activity 1 - Solution Proposals

During Activity 1, before presenting the Distributive Justice Principles, three out of four tables proposed a distribution that followed an Egalitarian approach (**Figure 21**). Two tables used Supplied Demand as their main indicator to define their flows and reached the exact same flow values and the other table used Supply per capita resulting in slightly different flow values. Table number 4 proposed that the distribution of water should not be Egalitarian since there are inequalities within the city. They thus proposed a distribution that prioritized water allocation to the SAs with higher marginalization and vulnerability such as SA3 and SA4.

	AqP1 - PP2 to PP3	AqP2 - PP3 to Pozos	AqP3 - Pozos to Toluquilla	AqP4 - Toluquilla to PP1
Table 1	0.2	-0.7	-0.6	-0.6
Table 2	0.2	-0.7	-0.6	-0.6
Table 3	0.2	-0.6	-0.6	-0.6
Table 4	0.5	-0.7	-1	-0.8

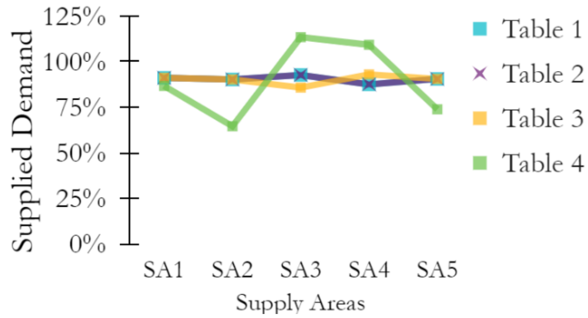


Figure 21. Results from workshop Activity 1

4.1.2 Restrictions and Considerations

Restrictions were defined as either limitations of the system that need to be considered on the model or the optimization or as non-negotiable objectives for the distribution policies. The most notorious restriction mentioned was the impossibility of pumping water between the SA3 - Pozos and the SA5 - Toluquilla due to insufficient pumping power to overcome the hydraulic head difference. This restriction was not considered in the initial model by R-Cities because the infrastructure was still new and the Water Authority was unaware of it. As this restriction is an unexpected feature of the AqP, the Water Authority was interested in understanding how it impacts the city's vulnerability and thus assessing if additional pumping capacity is .

Additionally, the participants of the workshop mentioned other considerations that could be useful for the design or implementation of the Distribution Policy. These considerations where summarized and clustered into the following topics:

- **System's evolution**
  - The PP3 will be expanded from the current capacity of around 2.1 m^3/s to 3 m^3/s to account for additional water flow coming from the connection of La Red Dam to the Calderon Dam and its respective Aqueduct.
  - There's an advanced negotiation to incorporate the Municipality of Tlajomulco as a new Supply Area under the SIAPA Network together with its current supply infrastructure and extraction permits of 2 m^3/s.

- **Distribution capacity/justice challenges**
  - The most marginalized communities usually live in areas with higher altitudes. Thus these are the most expensive and slowest neighbourhoods to provide water

for. Additionally, the system currently has little capacity to limit the outflow of water from the tanks. Thus, the neighbourhoods at lower altitudes and with higher incomes could consume the water from the tanks before it can be pumped to the water tanks at higher altitudes to be distributed in marginalized neighbourhoods. This highlights a characteristics of the system that limits the city's capacity to provide water to the most vulnerable neighbourhoods within each SA.

  - When there's insufficient municipal supply, the population and government rely on water trucks for water distribution. This represents a problem as they are not regulated, are expensive and highly pollutant.

- **Interactions with other policies and emergent measures**
  - Rainfall capture projects are growing all around the city, particularly in marginalized and hard-to-reach neighbourhoods.
  - Grey water reuse projects could support supply equity and are being promoted by the government and civil society.

- **Control over water demand/consumption**
  - The water authority could have more control over areas with higher public consumption.
  - It is legally allowed to modify water supply contracts with industry and services during emergencies but it is rarely applied.

These considerations were used in the following sections to shape the design and discussion about the implementation and future steps of the AqP's distribution policies.

Table 6. Restrictions for model or optimization

Consideration or limitation		Impact on	Source
Maximum capacity of Calderon La Red System to be increased to 3 m^3/s with the expansion of PP3	**INPUT**	Flow range (Calderón - la Red)	Workshop participant (Water Utility)
Maximum extraction from Chapala is 7.6 m^3/s as per the Federal Distribution Agreement of the Chapala Lake.		Flow range (Chapala)	Workshop participant (Water Utility)
Maximum capacity of 3.2 and 1 m^3/s for Pozos Well System and Toluquilla Well System respectively		Flow range (Pozos & Toluquilla)	R-Cities (2022)
Maximum flow of 1 m^3/s in the AqP segments	**LEVERS**	All AqP segments except segment 3 counterclockwise	Workshop participant (State Water Distribution directorate)
No flow between PP4 and PP5		AqP Segment 3 counter-clockwise	Workshop participant (State Water Distribution directorate)
50 l/day/person is the legal minimum supply in the State.	**OBJECTIVES**	Supply per capita	Workshop participant (Human Rights Lawyer)

4.1.3 Objectives

During Activity 2, each table designed an optimization formulation composed of objectives that were built using the Justice Objective cards (**Figure 15**) and the additional empty objective cards where participants could lay down objectives following their own structures. The objectives are summarized in **Table 7**.

Table 7. Objectives proposed in the workshop

	Principle	Indicator	Drought conditions
Table 1	Egalitarian	Supply per capita	All drought conditions
	Sufficientarian (100l)		
Table 2	Energy efficiency	Costs per m3/s per segment	Low drought
	Utilitarian	Supply per capita	
	Sufficientarian (non-specified)	Supplied demand	Mid drought
	Prioritarian (vulnerability Index)	Non-specified	Severe
Table 3	Egalitarian	Supply per capita	All drought conditions
Table 4	Utilitarian	Flow deficit	Low drought
	Sufficientarian (127l)	Supply per capita	
	Sufficientarian (100l)		Mid drought
	Sufficientarian (50l)		Severe
	Prioritarian (marginalization Index)	Non-specified	
	Egalitarian	Supplied demand	

By analysing these optimization formulations we can draw the following key conclusions:

Non-definitive and non-sufficient objective set

Although there are some repeated patterns, there's significant variance in the proposed formulations. Additionally, even though the objectives of diversity, quantity and level of influence of the participants were met, a single-event participatory process should not be considered sufficient to draw a conclusion about such a complex question as how water should be distributed during drought. Thus, the set of objectives resulting from this workshop is conceptualized as a diversity of valid potential solutions that can be used as the basis for further exploration. After exploration and additional participatory processes, it could be possible to converge towards a single set of objectives.

The Egalitarian principle with Supply per capita is the most recurrent

Most of the tables proposed that striving to distribute the same amount of water per person should be one of the objectives of the AqP. Two tables proposed this principle as part of a policy independent of drought conditions. Another one signalled it as necessary in case of a severe drought as it would be the most just and politically valuable policy due to the levelling down objection (Section 2.2). The preference for the Supply per capita indicator falls in line with a desire to have indicators that are relatable both to technical and non-technical actors. In contrast, indicators that are less relatable were less favoured as part of the formulations such as *Flow deficit* or *Supplied demand ratio*.

Prioritarian principle non-formalized
Whereas two tables proposed to prioritize water supply to the most vulnerable populations, none specified how exactly how to translate this principle into flow equations. Specifically, the tables proposed the use of the water vulnerability index (Díaz-Vázquez et al., 2023) and the Marginalization Index published by the Mexican Government, but none defined exactly how to aggregate it at an SA level or how to weight this indicator in order to prioritize water distribution. This operationalization was also not found in the literature as all other projects use initial currency distribution as the basis to define what parts to prioritize (Znabei, 2023), as opposed to this case where the priority is set by indicators independent of the initial amount of water that each SA has access to without using the AqP. Thus, no formal Prioritarian objective will be set in order not to implement unilateral numerical assumptions (such as assigning a weight to the vulnerability indicator). The Prioritarian approach will be defined as a compromise solution between the best performing score for an SA that the user wants to prioritise and the rest of the objectives they select on the decision support tool.

Cost objective is relevant for the Water Authority
The representatives of the Water Authority stressed the importance of considering the cost of the distribution of water as part of the policy objectives. In the final formulation, Table 2 which included the State Water Distribution Director, proposed that during low drought conditions, costs should be minimized along with a Utilitarian justice approach. However, when drought becomes more intense, water should be distributed fairly independently of its costs. They also stressed that pumping costs vary by segment and direction of the AqP due to distance and head difference. In this research, however, pumping costs were assumed to be equal for all segments in both directions as no data could be sourced to model these costs with more accuracy. Thus the cost objective was defined in its simplest form as the sum of the absolute values of the AqP flows with a min-max normalization. Future works could improve how this objective is modelled.

Sufficientarian principle associated with drought intensity (128, 100 or 50 l/day/person)
Half of the participants proposed a distribution that varies in relation to drought intensity. However, drought intensity was not clearly defined but just referred to intuitively. Following one of the research approaches of this thesis, which is to try to value and formalize intuitive knowledge through exploration and experimentation, this intuitive idea would be used as the basis to develop a context-specific, assumption-based Urban Drought Indicator (Section 4.2.1). This indicator can be used by decision makers to choose objectives.

Flow deficit indicator is less relevant
Although one table proposed an objective that includes the *Flow deficit* indicator, it is considered less relevant than the other two for the problem formulations. Additionally, within the discussions around the indicators few arguments supporting its usefulness for developing Distribution policies were mentioned. Thus, this indicator will not be used in further experimentation.

4.1.4 Indicators

Indicators incorporate more assumptions than what is often evident (Muller, 2018). How we decide to measure the state of a system or the impacts of a policy determines how such policy actually influences society (Lepri et al., 2017). To uncover those assumptions and support the process of choosing the right metrics to tackle the problem of water distribution in GDL, a significant part of the workshop discussions was guided towards the data and indicators that could be used in the distribution policy.

To frame this discussion, the three straight forward performance indicators that could be calculated with the GDL model were embedded in the **Interactive Scenario Exploration Tool.** These indicators were selected because they can be calculated using the GDL model, they reflect indicators often used in water management and don't include additional assumptions beyond those necessary to calculate water demand and water supply. The discussion held around these indicators is summarized as follows.

Supplied Demand

The Water Utility representatives stressed that they don't measure demand, that they can only estimate it based on historical commercial data and the outflows of the tanks distributed in the city. However, both of these potential methods to assess demand carry out uncertainties. Historic commercial data, on the one hand, has an information delay that could make it ill-suited for many management applications. Additionally, some of the clients of the water system don't have a water meter and they pay a fixed amount based on the consumption that is estimated for the characteristics of the client (SIAPA, 2014). The outflows of the tanks can provide a more immediate picture of how much water is being consumed, however due to leakage not all the output of the tanks reaches users. Additionally, not all tanks have telemetric systems, thus it is currently not viable to have a complete timely assessment of the outflows of the tanks and thus, a live indicator of water demand.

The *Supplied Demand* indicator was used by most participants during the first stage of Activity 1 as it was the one set by default in the Scenario Exploration Tool. However, as the participants started to explore the tool more and were challenged by the triggering questions, some switched to the *Supply per capita* indicator. The tables that continued using this indicator (tables 2 and 4) mentioned that this indicator, if properly calculated, could account for the differences in the consumption patterns in the areas and be useful for reaching Egalitarian distributions. In other words, we should strive to meet the same proportion of the demand between the SAs considering the specific needs of each SA. Thus, two areas could reach a desirable equal value of *Supplied Demand* while having significant differences of *Supply per capita* without being considered unfair as they have different needs. This interpretation of Egalitarianism could be further discussed in future works and could also depend on the drought intensity.

Some participants identified the variation in the distribution that results from using the *Supplied Demand* indicator and Supply per capita. This variation results from a difference in the consumption matrix of the SAs as shown in **Figure 22** that was included in the supplementary materials distributed to the participants (Appendix 6).

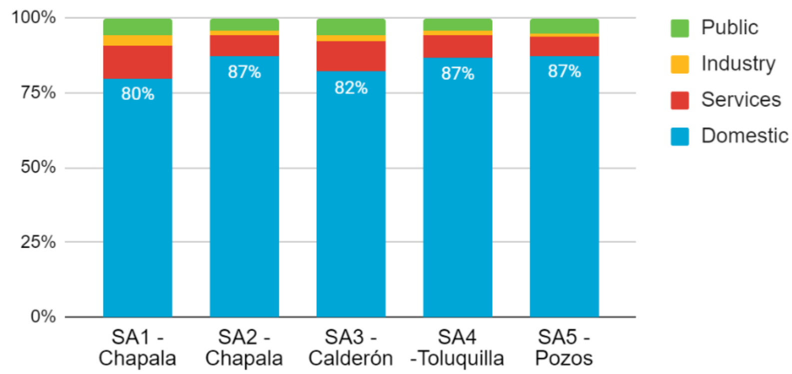


Figure 22. Relative water consumption per use 2020
Source: R-Cities (2022) with data from SIAPA

Supply per capita

This indicator was the most used in the problem formulations proposed by the participants. The reasons mentioned by participants for this preference is because it is the most relatable one as it is used both by water authorities and users. On the other hand, it was mentioned that this indicator hides the fact that some areas require more water per user than others. Thus trying to send the same amount of water per capita could distribute more or less water than what is actually needed by the inhabitants of the SAs.

It was also recognized that up to 20% of the water distributed to the SAs is not used by domestic consumers. Thus, the Supply per capita indicator does not exactly reflect how much water is actually available for the population. Nonetheless, it can still be used as a proxy of how much water is available per person in each SA. The possibility of subtracting the water consumption for non-domestic users was discussed. However, the consumption of these other uses might vary naturally during drought conditions or present seasonal variations. Additionally, one participant mentioned that the government is legally capable of halting water supply contracts during a drought emergency. Under these conditions, the Supply per capita indicator would more closely reflect the actual water available per person without considering uncertainties such as differences in grid efficiency between the SAs.

Flow deficit

This indicator, defined as the difference between the (modelled) demanded flow and the (modelled) supplied flow to users was the least used by participants during the workshop. The reasons behind this lack of preference could be related to the fact that it is an absolute metric in m^3/s and as the different SA consume different amounts, it is difficult to relate the absolute value of flow deficit to its potential societal impact in each SA. On the other hand, this is the only value that the Water Utility could measure by monitoring the inflow and outflow of their tanks. This highlights the preference for indicators that can be used both in a technical and social impact-oriented conversation rather than those more technically oriented.

4.2 Experimentation and Optimization

Using the insights from the participatory formulation stage, a series of computational experiments were conducted in order to build a reliable and useful Decision Support Tool. These experiments those focused on validating the mode; those focused on defining an optimization formulation and hyper-parameters that could provide optimal solutions for the set of objectives; and those focused on building an Urban Drought Indicator, designed to reflect the evolution in justice objectives based on drought conditions proposed by participants during the workshop.

4.2.2 Optimization Model Implementation

As the model had already been subject to a validation process by R-Cities (2022) and the Government of Guadalajara, the only validation conducted in this research focused on validating the Python implementation of the model and its optimization. To do so, an optimization run seeking to minimize the GINI coefficient for Supplied Demand Deficit (as Tables 2 and 3 were trying to do empirically) was conducted (**Table 8**) and it was compared with the one found by the participants of the workshop (**Figure 21**). As the results were identical considering rounding errors, the optimization implementation of the GDL model was considered valid.

Table 8. Comparison of numerical and participatory Egalitarian solution for the Drought 2021 scenario

	PP2 to PP3	PP3 to Pozos	Pozos to Toluquilla	Toluquilla to PP1
Numerical optimization	0.205	-0.664	-0.611	-0.638
Participatory workshop solution	0.2	-0.7	-0.6	-0.6

4.2.3 A-priori and a-posteriori Objectives Definition

Previous experiences with similar problems have shown that an a-posteriori approach for incorporating justice considerations into MOO can provide optimal results (Shavazipour et al., 2021; Znabei, 2023). In this approach, justice objectives might not be included in the optimization formulation but will be incorporated as filtering parameters on the resulting Pareto Set.

The decision support tool proposed requires that policy-makers can explore policies based on user-selected objectives. To facilitate this exploration process, avoiding having to run an optimization each time that the user selects a new set of objectives was paramount. Thus, an approach was selected where a single optimization would be run for any drought condition and the objectives would be incorporated as filtering parameters. This approach implies a trade-off as it might provide sub-optimal solutions for certain objectives.

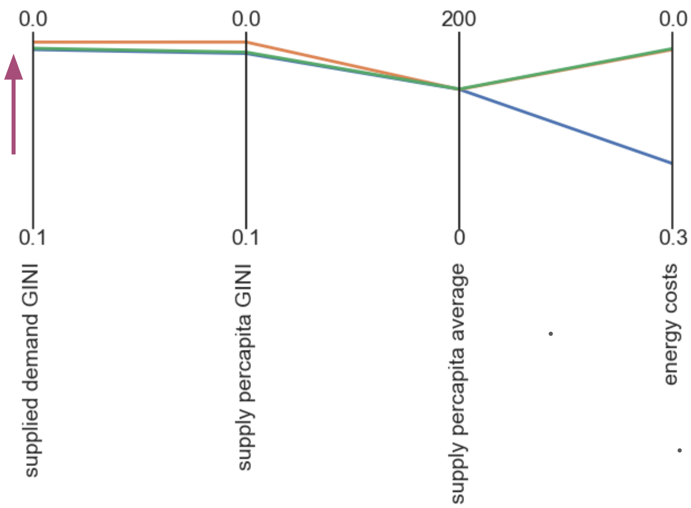
To assess this shortcoming of the a-posteriori approach and inform the selection of the optimization formulation, experiments were conducted comparing three optimization formulations across three representative scenarios (**Table 5**). These formulations were designed based on initial experimentation:

- **A-posteriori formulation**
  Only *Supplied Demand* deficit (5 objectives)

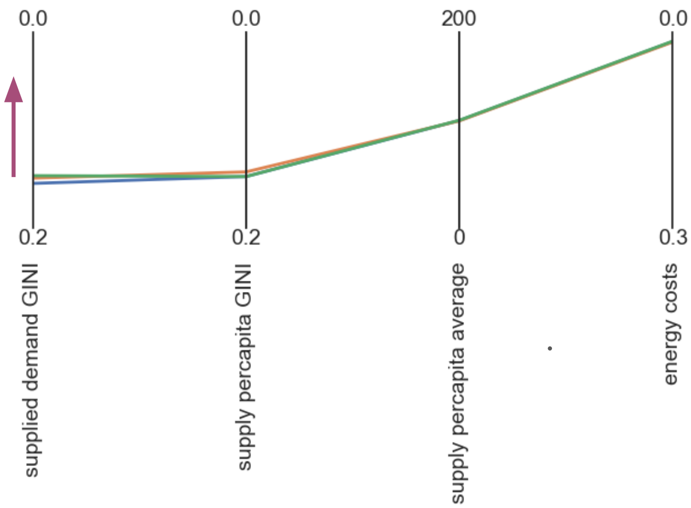
- **Mixed formulation**
  Supplied demand deficit, Supply per capita GINI and Energy costs (7 objectives)

- **A-priori formulation**
  Supplied demand deficit, Supplied demand GINI, Supply per capita GINI, Energy costs, Supplied demand average (9 objectives).

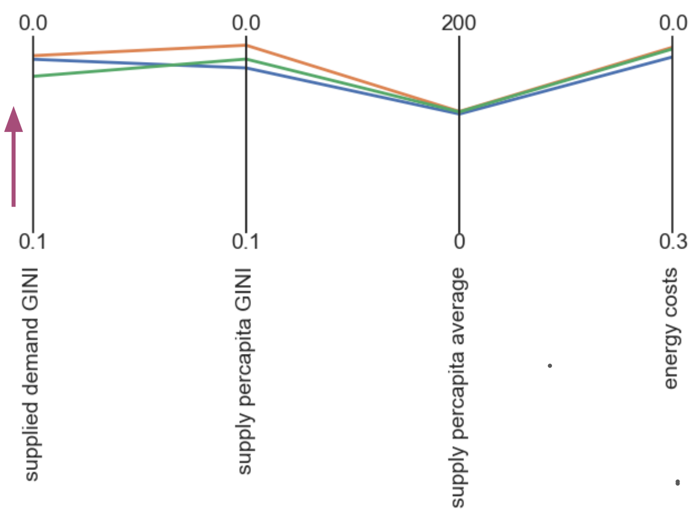
Figure 23 shows the scores of the best performing policy for each single objective across the three formulations and characteristic scenarios. This comparison enables us to assess whether these formulations are able to find policies with the same high scores for each objective. In other words, this comparison enables us to assess what would be the performance of the policies we would find if we filtered for the best-performing policy for any single objective with each formulation.



Scenario 2021 Drought			
Chapala	Calderon	Pozos	Toluquilla
7.1	0	2.2	0.4



Scenario Chapala Incident			
Chapala	Calderon	Pozos	Toluquilla
1.8	1	2.2	0.4



Scenario Groundwater Scarcity			
Chapala	Calderon	Pozos	Toluquilla
6.9	1	0.69	0.15

Figure 23. Scores of best-performing policies and a compromise policy across candidate formulations and representative scenarios

Note. Each line is associated with one Pareto Set. Each point represents the best-performing policy for each individual objective.

From this experiment we can draw the following key conclusions:

- **Egalitarian solutions can be found a-posteriori but benefit from an a-priori approach**
  It is notable that the formulation that does not include GINI-based objectives, and thus doesn't directly optimise for Egalitarian solutions, can still find similar performing policies to the formulations that do. This efficacy of all three formulations for finding Egalitarian solutions is valid for both formulations of the Egalitarian principle based on the *Supplied demand* and *Supply per capita* indicators. However, we can observe that there is a slight improvement in the GINI coefficient scores derived from incorporating these objectives in the optimization formulation (**Error! Reference source not found.**). This result is c onsistent with the findings of Znabei et al. (2023) who also found slight score improvements in GINI scores when incorporating the GINI coefficient as an a-priori objective. Moreover, the A-priori formulation generated better-performing Egalitarian solutions for the scenarios 2021 Drought and Groundwater scarcity. However, it is difficult to assess if this improvement is significant in terms of social impact.

- **Incorporating the *Energy Costs* objective is necessary**
  One of the clearest weaknesses of the simple formulation is its capacity to find energy-efficient policies. As this objective presents a high trade-off with the justice objectives it becomes particularly important to include it in the formulation. This result is mostly apparent in the 2021 Drought scenario.

- **Incorporating the Utilitarian objective is unnecessary**
  All three formulations generate an almost identical Supply per capita average score. Thus, incorporating the Utilitarian objective a-priori might not be relevant. This result is also consistent with the findings of Znabei et al. (2023) where the optimization formulation that included the Utilitarian objective generated almost identical scores as the reference formulation.

Compromise policies for three pairs of objectives were assessed to analyse the performance of the candidate formulations to provide desirable compromise solutions (**Figure 24**). The pairs of objectives assessed are the following:

- **Utilitarian** (*Supply per capita Average)* and **Energy costs**
  The need for this type of compromise policy for Low drought conditions was mentioned by Table 2 in the Workshop and proposed to tackle the 2021 Drought scenario.
- **Prioritarian for SA1 – PP1** (*Supplied Demand Deficit PP1)* & **Egalitarian** *(Supply per capita GINI)*
  This compromise policy is particularly relevant for scenarios where Chapala flow is low and there's a need to prioritize water supply to the most populated SA while balancing the supply for other SAs.
- **Egalitarian** (*Supply per capita GINI)* and **Energy costs**
  Although no Table wrote this particular compromise Policy in their final proposal, it was also discussed during the Workshop and could be used to tackle scenarios with Mid drought such as the Groundwater scarcity scenario.

The analysis is presented as scatter plots for each pair of objectives. A compromise policy located in the upper right corner would represent a policy that performs better for both objectives than those from other formulations. However, there are no such dominant policies, suggesting that no problem formulation can ensure that compromise policies with better scores on both objectives. On the other hand, the A-posteriori formulation generated a compromise policy for Egalitarian and Prioritarian that is dominated by the Mixed formulation (see centre plot in **Figure 24**).

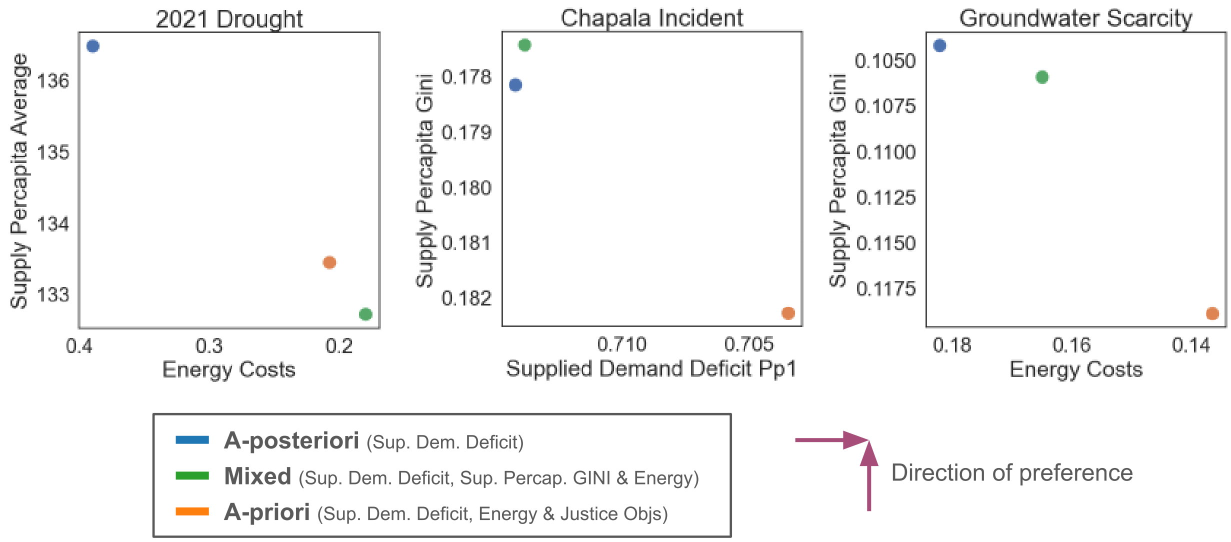


Figure 24. Compromise policies assessment of candidate problem formulations

We can also observe that the A-posteriori formulation consistently provided compromise policies with a poor energy costs score. And that the A-priori formulation provided poor scores for both Egalitarian objectives as well as the Utilitarian one.

Overall the *A-posteriori formulation* that does not include any justice-oriented objectives was discarded due to its shortcomings in terms of providing policies that can prioritize energy efficiency. The *A-priori formulation* did provided slightly higher performing policies for both Egalitarian objectives in the single objective assessment. However, it provided slightly lower scores on the Egalitarian objectives for the compromise policies. Although this formulation showed potential benefits in terms of single objective performance, it is unclear if these benefits can have a relevant societal impact considering system inaccuracies and uncertainties. Additionally, the increased complexity of this formulation increases the risk of non-convergence or other optimization artefacts. The *Mixed formulation* presents high scores on all single objectives and and presented some benefits in finding compromise policies for certain objectives and certain scenarios. Although it includes two more objectives than the simple formulation it still manages to run efficiently without any perceived issues. Thus, the *Mixed formulation* that includes *Supply demand deficit, Supply per capita GINI and Energy Costs* is considered the most suitable for this optimization framework.

4.2.4 Final Optimization Formulation and Settings

The optimisation algorithm necessary for this application must be able to find optimal policies for a variety of objectives across the whole drought conditions space. Additionally, it has to be sufficiently fast and reliable to ensure its usefulness for exploratory decision-making. An **epsilon of 0.04** was selected as it provides solutions with a sufficient resolution to find both optimal and compromise policies. The experiments showed that the algorithm converges at around 40,000 nfes (**Figure 25**). However, to mitigate the risks associated with this optimization approach, the number of **nfes was set to 50,000**.

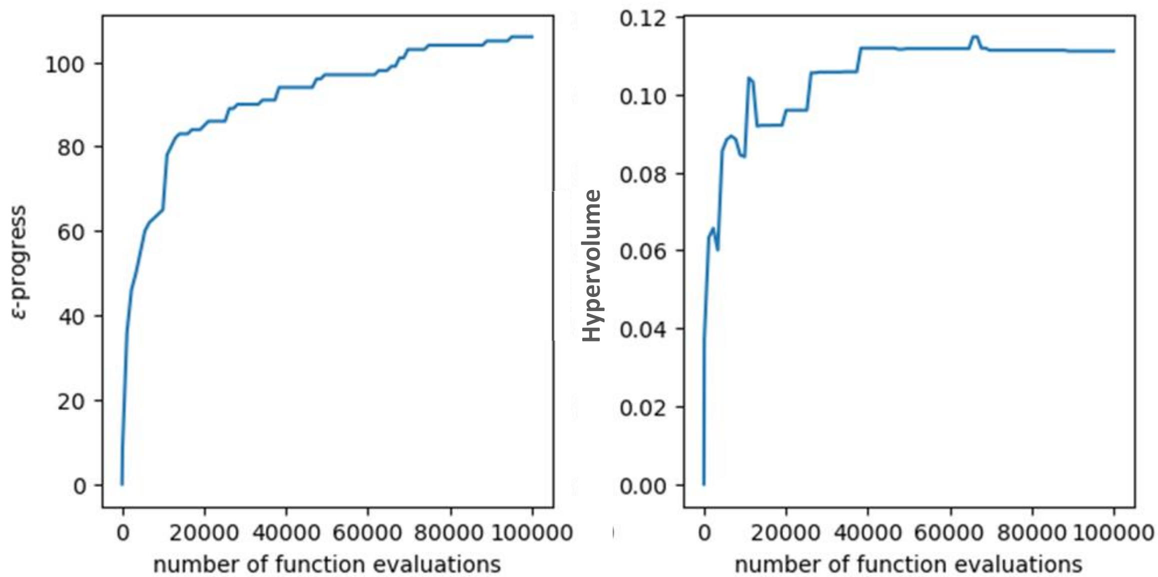


Figure 25. Convergence *for Supplied Demand Deficit, Supply per capita GINI and Energy costs*, Epsilon 0.04, 2021 drought scenario

The selected problem formulation includes ***Supplied Demand Deficit*** for each SA**, *Supply per capita GINI*** and ***Pumping costs*** adding up to **7 objectives** (see mathematical formulations in **Table 9**). The inclusion of the *Supply Per capita GINI* objective ensures that the most Egalitarian solution is found which was the most relevant objective proposed in the workshop. Finally, including the energy cost objective ensures that decision-makers can choose to find solutions that are also cost-efficient that would be otherwise not possible as this objective has significant trade-offs with the others.

Table 9. Operationalization of the objectives included in the final problem formulation
Note. The subscripts s and s' represent the SA. The subscript k represents the AqP segment and 4 is the maximum energy consumption where all segments are being used at max capacity.

Outcome	Formulation	Preference and aggregation
Supplied demand deficit [%]	$1 - \frac{Flow\ supplied\ to\ users_s}{population_s}$	**Minimizing at SA-level**
Supply per capita GINI	$\frac{\sum_{s=1}^{5}\sum_{s'=1}^{5}\lvert Supply\ per\ capita_s - Supply\ per\ capita_{s'}\rvert}{2 * 5^2 * Supply\ per\ capita_s}$	**Minimizing**
Energy consumption [%]	$\frac{\sum_{k=1}^{4}\lvert AqP\ flow_k\rvert}{4}$	**Minimizing at city-level**

The other justice-related objectives, such as the *Supply per capita average* (Utilitarian), the *Supplied demand GINI* (Egalitarian) were included only as filtering criteria (see **Table 3** for the formulations) and not as part of the problem formulation as including them did not show significant benefits (Section 4.2.3). No *Flow Deficit*-based indicator was incorporated as it was disfavoured by the participants of the workshop due to its lack of relatability.

4.3 Urban Drought Indicator Scenario Discovery

During the Scenario Exploration workshop, two out of four tables proposed distribution policies that depend on the drought conditions (**Table 7**). This means that they believe that the objectives behind the distribution policy of the AqP should change based on how intense the current water scarcity conditions are.

This idea that certain justice objectives might be more pertinent for certain drought or scarcity conditions started with a conversation with one of the supervisors from the thesis specialized in water ethics (N. Doorn, personal communication, 2024). To a certain extent, this idea falls in line with the Dynamic Adaptive Policy Pathways (Haasnoot et al., 2013) where policies react to changes in the environment as a means to deal with uncertainty. It is also in line with an intuitive proposal by Murphy & Gardoni (2008) who propose that the acceptability of risks should depend on the potential impacts of a hazard. On the other hand, no formulation of Distributive Justice Principles based on scarcity levels was found in the literature. However, following one of the approaches of this research of valuing and formalizing intuitive knowledge through exploration and experimentation, it was decided to include this component despite the lack of documented experiences for it.

Indeed, for this specific problem of water distribution, changing the distribution objectives based on the level of water scarcity could make sense. For example, Table 2 proposed that under low drought conditions, we should strive for maximizing the overall water Supply per capita and minimize pumping costs. However, once drought becomes more intense, minimizing pumping costs should no longer be a-priority. This potential justice interpretation based on the level of scarcity calls for the development of an indicator that could be used to assess the level of water scarcity and thus support decision-makers in selecting a pertinent distribution policy.

The National Meteorological Organization of Mexico publishes a meteorological drought index. However, in this case, the focus is to define an indicator of the risks for water supply shortage. This water scarcity might be associated with meteorological drought but could also be associated with other phenomena such as damage to the infrastructure[4]. Thus, it is necessary to build an indicator of urban water supply, also known as socio-economic drought, specific to GDL and the AqP that doesn't directly depend on meteorological conditions.

---

[4] Three weeks after the workshop, the pumping system of Chapala broke due to electric grid inestability halting the supply of the main water source of the city for around 4 days. See full news article at: https://www.tribuna.com.mx/mexico/2024/5/11/guadalajara-sin-agua-fallas-en-plantas-por-corte-de-energia-deja-seca-poblacion-368458.html

During the workshop, Table 4 suggested a Sufficientarian approach where the City should strive to supply a minimum of 142, 100 or 50 l/day/person to each SA depending on whether the drought conditions are Low, Mid or High respectively. Indeed, the AqP can often be used to ensure that all SA are above these thresholds. However, in some cases, there are no possible distribution policies for the AqP that can ensure these that these Sufficientarian objectives are met. With this assumption, an index can be built where the level of drought is defined by the probability that at least one SA will fall below each water supply threshold despite the best possible effort to avoid it using the AqP.

4.3.1 Methodology for Urban Drought Index

To formalize this index, we need to partition the space of possible water flows into the following subspaces:

- **No scarcity** space defined where all SA will likely be over **142** l/day/person (average Supply per capita for baseline conditions equivalent to 2020)
- **Low scarcity** space is where at least one SA is expected to be between **100** and **142** l/day/person
- **Mid scarcity** space is where at least one SA is expected to be between **50** and **100** l/day/person
- **High scarcity** space is where at least one SA is expected to be below **50** l/day/person

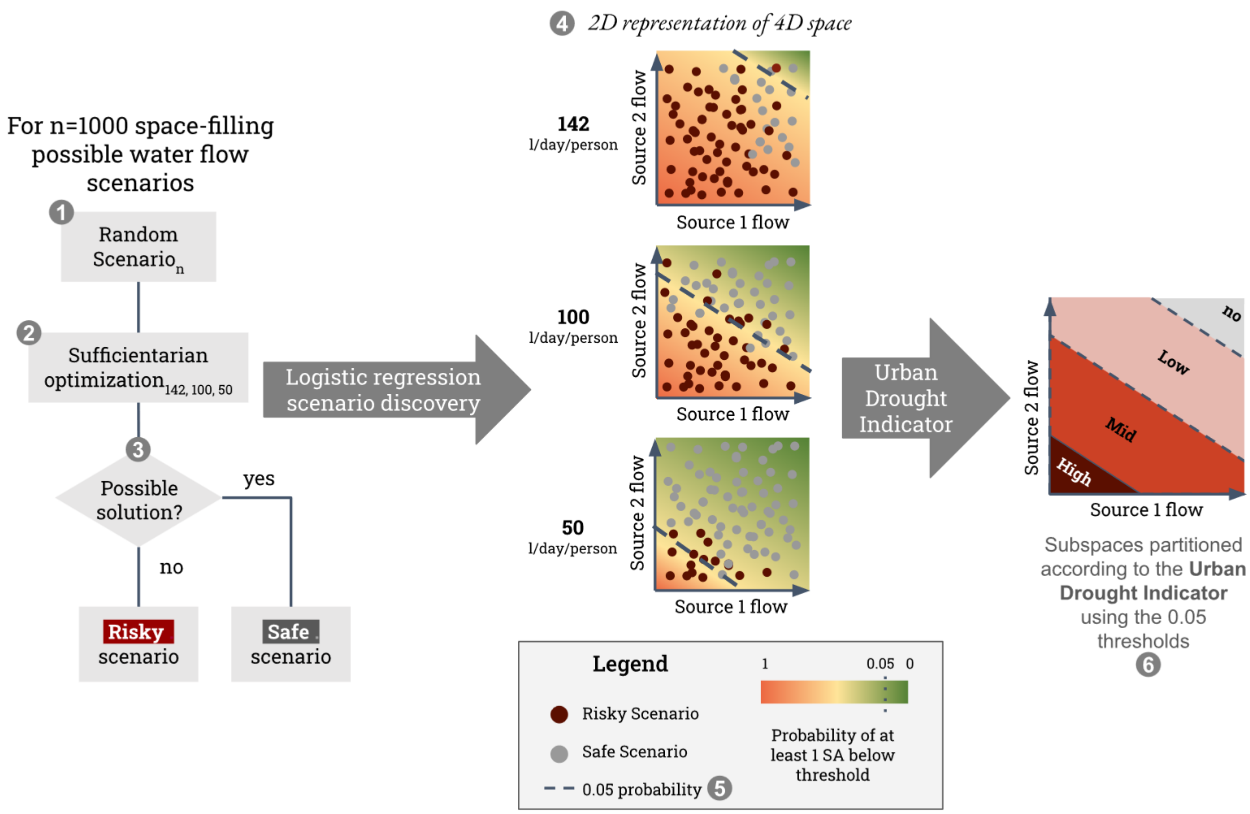


Figure 26. Schematic representation of the Urban Drought Indicator methodology

To find these subspaces, we first conduct a process to estimate the likelihood that at least one SA is summarized in **Figure 26** and follows the following steps:

1. Build a dataset of random, space-filling possible drought conditions. This was made using the Latin hyper-cube method as suggested by Kwakkel (2019) using a minimum of 0 m^3/s and the maximum possible flow for each source as described in **Table 10**.
2. Conduct a single objective optimization for each scenario to minimize the amount of SAs under each threshold.
3. If the optimization could find a solution where no SA falls below each threshold, it was labelled as safe for that threshold, else it was labelled as risky.
4. Conduct scenario discovery using a logistic regression for the two types of scenarios to identify the risky space for each threshold.
   This process generates one equation for each threshold that estimates the probability of falling below the threshold based on the four water flows. A sample visualization of these equations using pairwise plots for representing the 4D gradient can be seen in **Figure 27**.
5. Define a probability threshold after which we consider that this subspace is considered risky of falling below the threshold. This probability threshold is initially set to 0.05 meaning that there's a 95% reliability index as proposed by Quinn et al. (2018).
6. Use the hypersurface associated with the 0.05 probability for each Sufficientarian threshold to partition the space of water flows into no, Low, Mid and High drought.

This Indicator was incorporated into an algorithmic design that uses the logistic equations to calculate the probability for each threshold. The algorithm first assesses the 50 l/day/person and if the probability of not meeting this threshold is higher than 0.05 then it determines it is a High drought. Else it continues with the following thresholds. If the probability of falling below 142 is lower than 0.05 then it is assumed that there's no drought conditions.

Table 10. Maximum flows for each source

Source	Maximum flow [m^3/s]	Justificationt6ghyjui
Chapala Lake	**7.6**	The maximum yearly average flow that can be extracted from Chapala Lake by the water authority of Guadalajara is defined by the Distribution Agreement is 7.6 m^3/s. However, this distribution agreement could change, or the authority might be allowed to extract more during emergency situations.
Calderon-La Red System	**3**	The Calderon Aqueduct that connects the Calderon-La red system to the PP3 has a maximum design capacity of 3 m^3/s. However, to further exploit the city's extraction permits from the Verde River.
Pozos Well System	**3.2**	The Pozos wells system is composed of many decentralized wells and springs thus the maximum capacity is difficult to assess. The maximum monthly value flow between 2006 and 2021 is 3.2 m^3/s extracted in March 2007. During drought conditions, the water authority has temporarily increased its well extraction flows to combat scarcity.
Toluquilla Well System	**1**	This well system is composed of a certain number of wells that are channelled to the Toluquilla Aqueduct and then pumped to the PP4 that has a maximum capacity of 1 m^3/s.

Sources: Data submitted by SIAPA and processed and reported by R-Cities (2022)

4.3.2 Analysis and Sensitivity of Urban Drought Indicator

Figure 27 shows a pairwise two-dimensional representation of the logistic regressions of the scenarios above and under each Sufficientarian threshold. The first row shows the combination of water flows where no distribution policy of the AqP can ensure that all SAs have at least 142 l/day/person which is the current average *Supply per capita.* It can be observed that a slight deviation of the current conditions will represent the start of a Low drought intensity. The High drought intensity would begin when the water sources fall to levels well under the normal conditions, for example when the Chapala flow falls below 2 m^3/s.

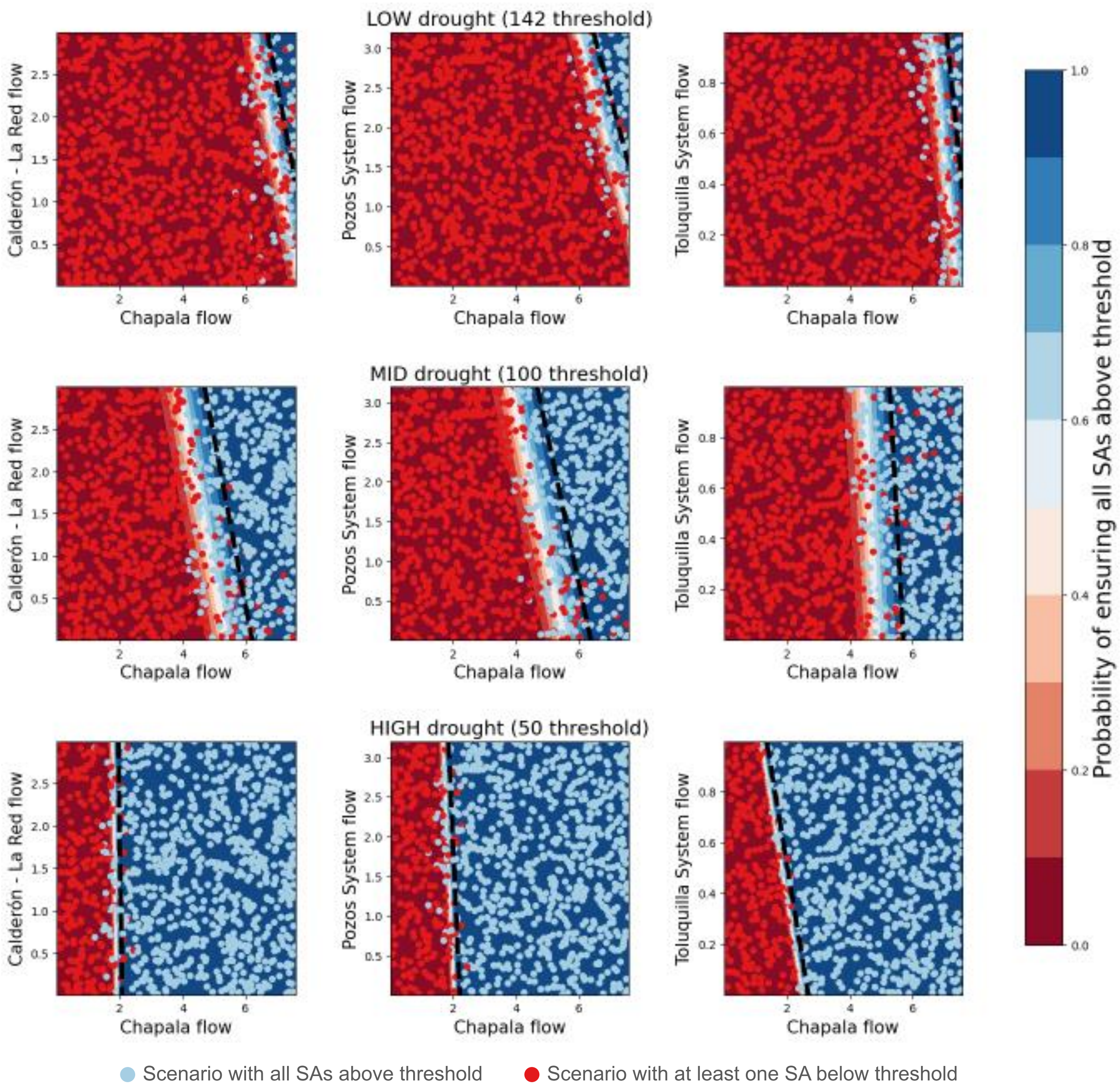


Figure 27. Logistic regression of the risk of falling below the 50, 100 and 142 l/day/person Sufficientarian thresholds for GDL's water sources flows in m^3/s

Note. The dotted line shows a 0.05 probability representing a 95% confidence interval of not falling into a risky subspace for each threshold. These lines represent the hyperplanes used to partition the subspace for the Urban Drought Indicator.

We can observe that for the Low and Mid drought, there is more diffusion of risky scenarios in the area deemed safe by the logistic regression. This suggests that the logistic regression for the 142 threshold is less precise than for the 50 l/day/person threshold where a clearer separation can be observed. For the 50 l/day/person threshold, the transition is almost immediate suggesting that there's a very accentuated transition between risky and safe subspaces and thus the logistic regression is more accurate. This can also be observed by how thin the transition area between the blue and red colours is . This transition represents the slope of the sigmoid that is lowest for the Mid drought and highest for the High drought.

We can also observe different slopes from the probability gradient across sources and thresholds. This suggests that some sources have a higher influence on the city's ability to meet each threshold and that certain levels of drought might be influenced primarily by one variable while others present a more complex behaviour. In general, we can observe that the Chapala Lake is the source that most influences the ability to meet all three thresholds by how all lines are closer to a vertical line. Most notably, the High drought subspace is almost entirely determined by the flow from Chapala with a smaller influence from the Toluquilla well system. This can be observed by the almost vertical lines for the subplots of Calderon la Red and Pozos System for the 50l/day/person threshold.

To further explore which sources have the largest influence on each failure mode, and thus are more critical, we extract the coefficients or slopes from each logistic regression as sensitivity indicators (**Table 12**). Thus if Chapala fails, only Toluquilla could provide water to the SA1 – PP1. Although a longlasting failure of Chapala, Mexico's largest water reservoir, is unlikely, this result highlights how the current restriction increases the vulnerability of the city to high droughts. This result also highlights the criticality of the Chapala Aqueduct as it is the infrastructure that has the largest impact on urban water scarcity risks. Indeed R-Cities (2022) highlighted the importance of maintenance and updates to this infrastructure as a key action to increase the city's resilience to drought.

We can observe that the Chapala Lake has the highest sensitivity in Low and Mid drought and close to the highest for High drought. This dominance of the Chapala Lake to determine the risks of water scarcity was expected as this source constitutes around 65% of the water supply under normal conditions (R-Cities, 2022). Additionally, this source supplies two SAs. Thus, it can more easily provide water to other SAs in need. However, it is notable that for the High drought scenario, the SA4 Toluquilla has a higher sensitivity. This could be due to the current This can be due to restriction of the system that was highlighted during the workshop where the installed pumping capacity is insufficient to pump water from the SA Pozos to Toluquilla (**Figure 28**) due to a significant hydraulic head difference.

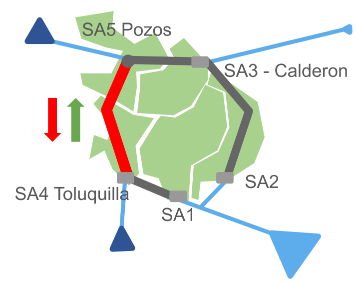


Figure 28. Current restriction on the flow from Pozos to Toluquilla

Thus if Chapala fails, only Toluquilla could provide water to the SA1. Although a complete failure of Chapala, Mexico's largest water reservoir, is unlikely, this result highlights how the current restriction increases the vulnerability of the city to high droughts. This result also highlights the criticality of the Chapala Aqueduct as it is the infrastructure that has the largest impact on urban water scarcity risks. Indeed R-Cities (2022) highlighted the importance of maintenance and updates to this infrastructure as a key action to increase the city's resilience to drought.

Table 11. Regression coefficients for each threshold

	Low drought (142)	Mid drought (100)	High drought (50)
Chapala	-6.3	-3.6	-18.7
Calderon La Red System	-3.2	-1.8	-0.8
Pozos Well System	-4.2	-1.9	-2.1
Toluquilla Well System	-5.1	-1.5	-24.7
Pseudo R^2	**0.77**	**0.83**	**0.96**

By comparing the pseudo-R^2 values, we can comment on how well each regression fits the data. We can observe that for the high drought scenario, the pseudo-R^2 is 0.95, suggesting that the drought indicator is capable of predicting almost perfectly if certain drought conditions might push an SA below 50 l/day/person. On the other hand, the model presents a lower accuracy for the low drought conditions with a pseudo-R^2 of 0.81 and 0.77. These results are in line with the observations from **Figure 27**. A validation analysis was conducted to further study the efficacy of the indicator.

4.3.3 Validation

To validate this Urban Drought Indicator, we compared how each scenario was labelled in the optimization with the estimate provided by the Urban Drought Indicator. Using this comparison we counted the following possible outcomes for each threshold:

- **False positive**: Labelled as risky and located in the safe subspace.
- **False negative**: Labelled as safe and located in the risky space.

The results from this validation procedure can be observed in **Table 12** in terms of the ratio of correctly and incorrectly identified scenarios by the Urban Drought Indicator. We can observe that for both High and Mid droughts, the errors are below 3%, highlighting a good fit of the indicator to predict drought intensity. However, the error for Low drought scenarios is larger.

Table 12. Proportion of incorrectly predicted scenarios by the Urban Drought Indicator

	High drought	Mid drought	Low drought
False positive	**0.3%**	**2.1%**	**5.5%**
False negative	**0.2%**	**1.5%**	**4.8%**

As we are dealing with a risk assessment, we consider that false negative scenarios, where the drought conditions are worse than the indicator predicts, represent the highest danger in terms of decision-making for the water supply. Even if the false negative is marginally lower than the false positive for low drought, it is still considered that this issue should be addressed to avoid unexpected risks and increase the reliability of the indicator and the system. Other methods of scenario discovery could provide better results. However, since these errors are only significant for the lower drought conditions the shortcomings of the indicator could also be dealt with policy rather than numerically.

4.4 Decision Support for Distribution Policies

Once the final hyper-parameters and problem formulation were defined based on the experiments presented in Section 4.2.4, an algorithm to conduct the optimizations and filter for preferred policies was developed. This algorithm follows the conceptual layout presented in **Figure 18** and was mounted in a mock-up of the Decision Support Tool (DST) for Distribution Policies of the Aquapheric available at: https://gdl-aqp.streamlit.app. To communicate the use and usefulness of the DST three illustrative cases based on the representative scenarios and using the formulations from the workshop (**Table 7**) are discussed below.

The Tool lets users select a scenario and provides a small explanation of each one. Then, the user can load the scenario to visualize the current drought conditions in term of the Supply per capita to each SA. Additionally, the system calculates the Urban Drought Indicator that can be used to advise on the selection of objectives. Finally, different objectives can be selected, and the system will provide the best performing and compromise solution for the selected objectives. The Sufficientarian thresholds are also visualized to facilitate the selection of policies.

Figure 29 shows the policies that the DST would propose for dealing with the 2021 Drought by optimizing for an Egalitarian approach based on the *Supplied Demand* indicator and for *Energy costs* as workshop Table 2 proposed for low drought conditions such as this one. We can observe that the tool generates the most Egalitarian policy found empirically during the workshop, serving also as validation of this Tool. Additionally, we find a compromise policy that maintains a low GINI while only using 20% of the AqP's energy as opposed to 50% for the purely Egalitarian solution.

As mentioned in Section 4.1, the Prioritarian principle could not be formalized during the workshop. Moreover, this principle has rarely been operationalized using indicators that don't include the currency that is being distributed. For example, in this case participants proposed that water supply should be prioritized based on Marginalization level, not on any water supply indicator. Despite not having a formal formulation it was decided to incorporate a mechanism to prioritize SAs since it was extensively discussed during the workshop. Thus, a simple implementation of Prioritarianism was included where the user can filter for the policy that maximizes the supply of water for any SA. In on itself, this implementation is highly flawed, as simply increasing the flow towards a SA often leads to risk transfers. However, these Prioritarian objectives in combination with other objectives can result in valuable compromise solutions as shown in **Figure 31**.

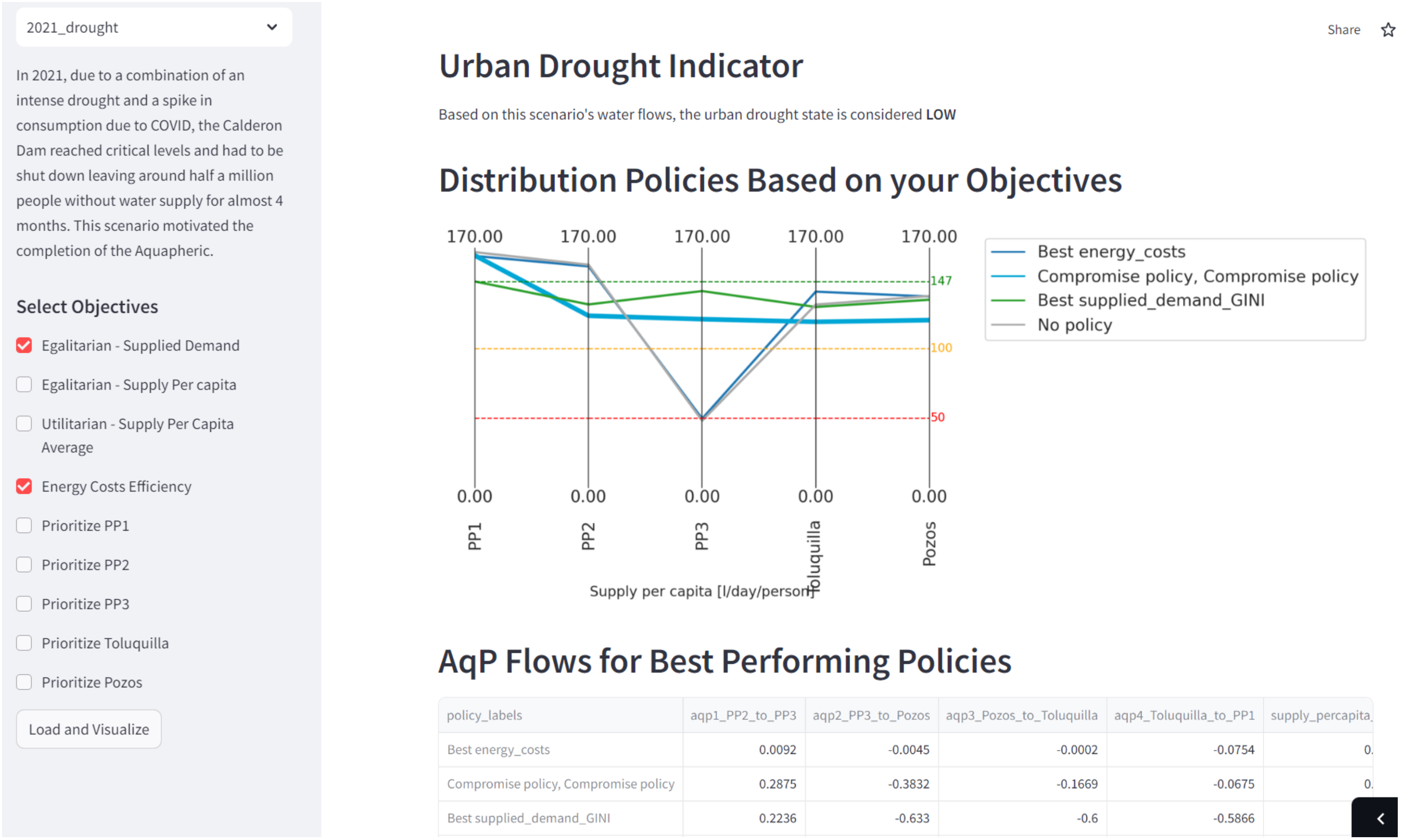


Figure 29. Snapshot of the AQP DST for the 2021 Drought with an Egalitarian and Energy cost objectives

For the Chapala Incident scenario, where almost no water was flowing from the Chapala Lake, the Urban Drought Indicator suggests a High drought intensity. Under these circumstances, an Egalitarian approach might not be ideal as it would imply taking even more water from the SA1 – PP1 that is already facing severe water scarcity (**Figure 30**). The reason why under this scenario, an Egalitarian distribution is unattainable is due to the current hydraulic limitation that doesn't allow water to flow from the SA5 – Pozos towards the SA1 – PP1.

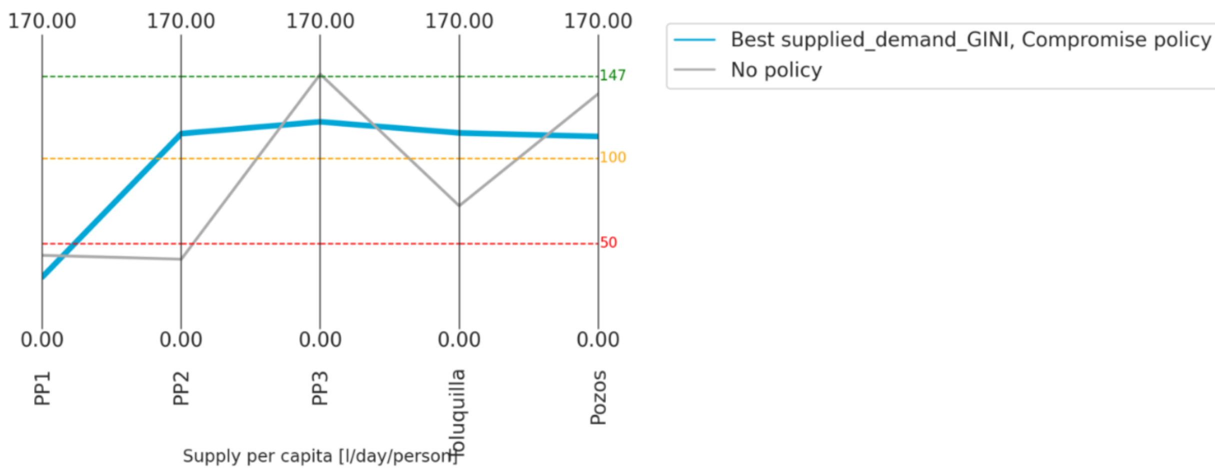


Figure 30. An Egalitarian approach to deal with the Chapala Incident scenario

For this scenario it would be more advisable to prioritize supply to the SA with the worst conditions, in this case the SA1 – PP1 (**Figure 31**). However, we observe that if we only prioritize this SA (orange line) we transfer the burden to SA4 – Toluquilla. Thus, a compromise solution that prioritizes the supply to SA1 – PP1 and the Egalitarian approach is more desirable (**Figure 31**).

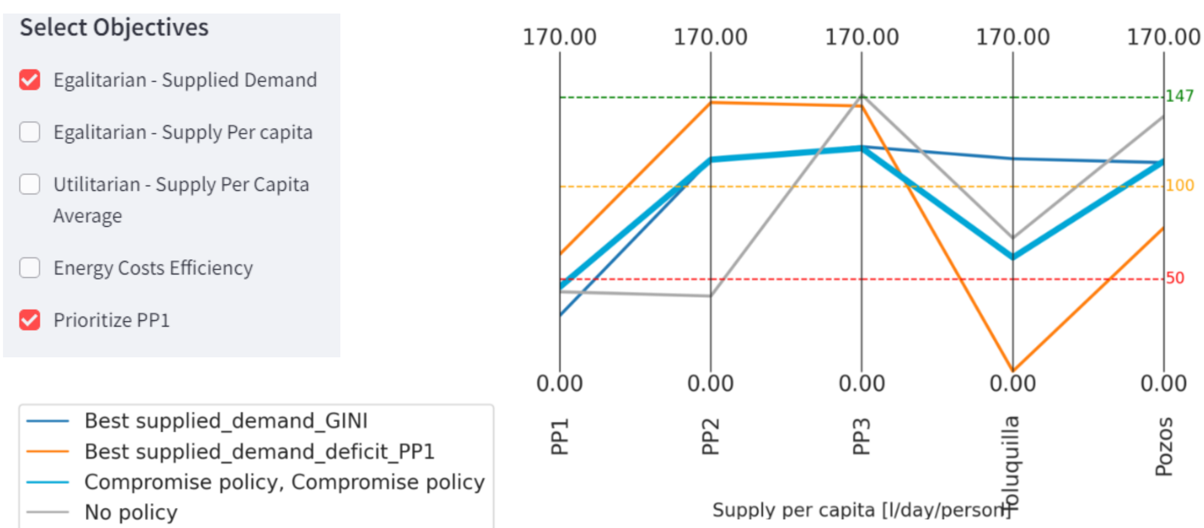


Figure 31. Prioritarian approach for PP1 and Toluquilla for dealing with Chapala Incident scenario

4.5 Results Summary

The **Participatory problem formulation** provided insights into how fairness can be interpreted for this decision-making problem as well as elements to conduct experiments that can lead towards developing an optimization-based Decision Support Tool. Participants of the workshop proposed a range of objectives that reflected the complexity and context-specific nature of fairness in water distribution. Notably, half of the participants suggested that objectives should evolve with worsening drought conditions. For example, under Low drought conditions, some participants proposed that cost considerations could be included in the AqP's objectives. However, as drought intensity increases, the focus should shift towards supplying the most vulnerable populations, who have limited access to alternative water sources such as water trucks or rainfall capture systems. This intuitive relationship between distribution priorities and drought intensity highlighted the need for an Urban Drought Indicator that reflects context-specific water scarcity.

The workshop participants proposed formulations that included all four Distributive Justice Principles. The Egalitarian principle, which emphasizes equal water distribution per capita, was the most favored, with one group suggesting it should be the sole guiding principle for the AqP. Participants also acknowledged the importance of prioritizing water supply for the most vulnerable populations, although they did not reach a consensus on how to numerically implement the Prioritarian principle using indicators like the Marginalization Index. The Sufficientarian principle was invoked to ensure that minimum water supply levels, reflecting the Human Right to water. The Utilitarian principle, focusing on the greatest good for the greatest number, was proposed only as a practical and politically viable option under Low drought conditions. Additionally, one table proposed that a pumping cost objective should be included for low drought conditions. This was the only non-justice-related objective proposed.

During the workshop, several system constraints and considerations were identified, which have significant implications for how fairness can be operationalized in water distribution using the AqP. A key restriction discussed was the technical limitation preventing the transfer of water between two SA due to insufficient pumping capacity. This restriction was integrated into the optimization model as an optimization constraint.

Participants also highlighted the challenge of providing water to marginalized communities situated at higher altitudes, where distribution is more expensive and slower due to system limitations. This challenge underscores some of the key limitations of any distribution policy for the AqP in addressing the systemic inequity of Guadalajara's water supply system. Thus highlighting the need for additional infrastructure and policy interventions that also consider fairness during drought conditions to complement the Distribution Policy proposed.

A major objective of the workshop was to understand the social and technical implications of the selection of indicators for the AqP's objectives. It was noted that the current data limitations and characteristic of the system, such as inaccurate demand estimates based on historical data and the lack of comprehensive real-time monitoring, introduce significant uncertainties that limit the AqP's potential impact. Recent efforts in improving such monitoring were also mentioned highlighting the importance of building a framework that could integrate future data sources.

The main characteristic that influenced the selection of indicators was their relatability. For example, the *Flow Deficit* is the only indicator that can be measured by the water authority, however, it was used only for one objective as it is more difficult to foresee the potential societal impacts associated with a numerical value of Flow Deficit in m^3/s. The *Supply per capita* indicator, on the other hand, was the most used one as it is meaningful for both technical and social stakeholders.

A significant part of the discussion focused on understanding what does each indicator reflect and under what conditions should they be used to operationalize justice. For the Sufficientarian principles, the *Supply per capita* indicator was favored. For the Egalitarian Principle, some participants proposed using *Supply per capita* in order to supply the same amount of water to everyone. However, it was noted that some users require more or less than others, and thus, a *Supplied Demand* indicator based on water demand data at an SA-level (contrary to the current city-level average water demand per capita), could be more useful. However, this approach might not hold true as drought intensifies and the differences in water consumption per capita could become less tolerable. The *Flow deficit* indicator was mentioned in only one formulation because participants found it challenging to relate a flow deficit value to a potential societal impact. Thus this indicator was excluded from the following stages.

In the **Experimentation and Optimization stage**, a series of experiments were conducted using the inputs from the Participatory Formulation stage. First, the model from Guadalajara's water distribution system (the GDL model) was implemented into a Python-based optimization framework. The limitations and restrictions mentioned in the literature and the workshop were included such as maximum possible flows from the sources and the lack of pumping capacity in one direction of one segment of the AqP.

An analysis of three candidate problem formulations was conducted to select one that can provide the best-performing policies for each objective as well as relevant compromise policies for pairs of objectives. The a-posteriori formulation that did not include any justice-related objective was discarded due to its inefficacy in providing policies with high energy efficiency. The A-priori formulation, which included all the objectives available was discarded because the additional complexity did not provided significant benefits. Finally, a mixed formulation that includes *Supplied Demand Deficit* of each SA and *Supply per capita GINI* (the most used objective in the workshop) as well as *Energy costs* (to ensure that energy efficient policies can be found) was selected. This formulation was tested for convergence to ensure that it can reliably find the desired policies.

An Urban Drought Indicator was developed as a response to the intuitive idea that objectives for water distribution should evolve as drought conditions worsen. This Indicator reflects the probability that considering the flows of water from the four sources and despite the use of the AqP, at least one SA will fall below 142, 100 or 50 l/day/person for a Low, Mid or High drought respectively. These thresholds were mentioned in the workshop, the first being the average conditions and the two others are related to the Human Right to water.

Finally, in the **Decision Support** stage a Decision Support Tool that enables policy-makers to explore how different sets of objectives translate to distribution policies was developed. Using this Tool, policymakers can propose what objectives should be used under what level of the Urban Drought Indicator. This process could take place in a future participatory workshop. Three characteristic drought scenarios were mounted on the DST to facilitate this discussion around three possible situations with highly different causes and impacts. This tool follows a conceptual design that aims at enabling continuous learning and improvement by enabling policy-makers to test different objectives and update key elements of the model.

5. Discussion

5.1 Towards Distribution Policies for the Aquapheric

This thesis set out to explore how to design distribution policies for Guadalajara's Aquapheric, to ensure just water distribution during drought conditions. The main research question guiding this study was:

RQ: *How can we design distribution policies for Guadalajara's Aquapheric to ensure just water distribution during drought?*

To answer this overarching question, the research was structured around three sub-research questions:

SRQ1: How can local stakeholders be engaged in the process of identifying how fairness should be interpreted and operationalized for water distribution under drought conditions?

SRQ2: What multi-objective optimization formulation can reliably find optimal policies for different objectives and drought conditions?

SRQ3: How can we support the selection process of optimal distribution policies by the local authorities considering both value and system uncertainties?

In the following discussion, the findings related to each of these sub-questions are analyzed. These findings lead to a comprehensive understanding of how the proposed approach can contribute to fair water distribution under scarcity conditions in Guadalajara.

5.1.1 Participatory Problem Formulation for Justice Exploration

To address the challenge of distributing water fairly during times of scarcity, it is essential to first explore different interpretations of what justice is and to understand the system's constraints that influence how water can be distributed. To achieve this, a participatory process was implemented to identify different understandings of the 'right' approach to water distribution during drought conditions. This process was grounded in Distributive Justice Principles, which effectively provided a common vocabulary and conceptual framework to guide the discussions.

The participatory workshop, held in Guadalajara in April 2024, met all of its goals related to its process and outcomes. 26 high-level representatives of governmental institutions, academic stakeholders, and international organizations participated in the 3 hours workshop. The feedback from the participants was mostly positive, highlighting their high level of engagement, appreciation for the facilitation tools used and interest in the methods proposed (Appendix 8). The workshop design and resources promoted engaging discussions that yielded valuable insights into the interpretation and operationalization of fairness in water distribution.

The workshop successfully gathered a diverse range of perspectives, which led to a nuanced understanding of how fairness could be interpreted and applied in Guadalajara's water distribution system. It is important to note that this process highlights just how complex it is to determine what fairness is in water distribution. As such, no universal definition of what justice is for urban water distribution can be drawn and no single participatory workshop can be operationalized, just as the conclusions of the workshop are bound to change with time and thus should not be set in stone.

Indeed, the diversity of the objectives in terms of water distribution justice put forth by participants reflects the need for a flexible approach. The capacity to adapt to the evolution of the discussions around justice in water distribution as well as the evolution of the system is key. The proposed Urban Drought Indicator, for instance, offers a first approach to a dynamic adjustment of the distribution priorities based on the severity of water scarcity. Another example of the importance of enabling a continuous improvement of this approach is the lack of consensus on how to implement vulnerability-based prioritization of water distribution.

This experience underscores the importance of involving local stakeholders in knowledge co-creation processes to tackle problems with value-related and system uncertainty. In this research, we present an experience of a successful participatory formulation for a Multi-Objective Optimization Problem based on the Distributive Justice Principles. Thus, we offer a valuable contribution to a more grounded and contextually relevant understanding of fairness that aligns with the system's capacities and that takes into account the concerns of its designers, operators and users.

5.1.2 Multi-Objective Optimization for Decision-Making

During the workshop, participants mentioned the difficulty of translating ethical discussions into actual flow values. Participants eventually managed to find the most Egalitarian distribution for one scenario in this case. However, applying a similar empirical process could turn out to be more challenging for other justice approaches or under more challenging scenarios. The proposed optimization framework using the GDL model, and a variety of candidate justice objectives and an energy objective proved effective in tackling this limitation of the empirical approach.

As a result of the diversity of solutions proposed in the workshop, it was decided that the optimization framework should enable a quick exploration of different combinations of objectives. To do so, an optimization framework was designed where an optimization is run for a fixed formulation, and the objectives selected by policymakers are used to filter the Pareto set. Avoiding having to run an optimization each time a policymaker wants to explore a new set of objectives will be beneficial. However, as the distribution policies can have a significant societal impact, it is paramount that the solutions found with this approach represent the best-performing policies possible for the selected objectives. The analysis conducted compared three candidate problem formulations and concluded that Mixed formulation that incorporates the *Supplied Demand Deficit* SA-level objectives and the two key city-level objectives, *Supply per capita GINI* and *Energy Cost*, is enough to provide the desired accuracy while ensuring a fast and reliable optimization. On the other hand, it is recognized that this analysis was only performed for three scenarios, and thus future works could expand the analysis to a broader range of the uncertainty space. Additionally, the results related to the capacity of this problem formulation to provide high-performing compromise solutions were not conclusive calling for additional analyses.

As half of the participants proposed a problem formulation that depends on drought intensity, it was necessary to develop such an indicator. The Urban Drought Indicator was designed by conducting a logistic regression-based scenario discovery to find the subspaces where the three Sufficientarian objectives become non-attainable. This indicator proved highly accurate at predicting under what conditions the AqP is unable to ensure that all SAs have at least 142, 100 or 50 l/day/person, with a maximum proportion of false negatives under 5%. Despite this accuracy, more work could be done to improve the indicator's accuracy. Additionally, a validation process with local authorities is necessary to improve the usefulness of this indicator.

5.1.3 Decision Support for Continuous Learning and Knowledge Co-Creation

After conducting the Participatory formulation and the Experimentation stages, a Decision Support Tool (DST) was designed. This Tool does not intend to propose a single definitive policy. Rather, it focuses on enabling policymakers to explore how different combinations of objectives can be translated into distribution policies. Such a discussion was not held during the participatory workshop because there was still the need to refine the formulation of the GDL optimization model and build a bank of pertinent objectives. The DST mock-up can facilitate a convergent participatory process where policymakers can define what objectives should guide the design of distribution policies under what conditions. The Urban Drought Indicator could be used in this process as it provides insights on water scarcity specific to Guadalajara's unique water system.

The Decision Support Tool for Guadalajara's Aquapheric was designed to help representatives of different sectors to discuss what objectives should be used in what conditions by observing its impacts on water supply for the SAs. The current mock-up of the Tool available online serves as a proof of concept of this Framework. This Tool could be used in a participatory workshop such as the Interactive Policy Exploration Workshop proposed by Gold et al. (2023) to define a Distribution Policy for the AqP.

Additionally, the water supply system and its governance (including the frameworks, arrangements, persons and institutions) are in continuous evolution. For this DST to be useful, it is necessary that it can accommodate such changes. For this, an approach that can integrate new data and facilitate continuous learning by repeated cycles of knowledge co-creation was favoured. Defining the uncertainties in an easy-to-update CSV file, such as the grid's efficiency and the population in each SA, can facilitate the inclusion of new data. Additionally, by using a simple model that can be run on a desk computer also facilitates this potential future evolution and improvements.

5.1.4 Conclusion

In this thesis project, a simulation and participatory-based process that integrated methods from Decision Making under Deep Uncertainty such as Multi-Objective Optimization and the Distributive Justice Principles has been developed and implemented. The three stages of analysis conducted in this thesis contribute to a framework that can enable policymakers to design and support the selection of fair distribution policies for Guadalajara's Aquapheric under drought.

The participatory process revealed the complexity of interpreting what fairness would look like in water distribution and developing useful mathematical operationalizations. The use of the Distributive Justice Principles framework proved to be effective in guiding justice-centred discussions by offering a shared vocabulary between stakeholders from diverse technical backgrounds. The involvement of a diverse range of stakeholders, government officials, academic experts, and representatives from international organizations was instrumental in identifying a nuanced interpretation of justice and the system constraints that shape water distribution policies. The workshop highlighted the need for a flexible and context-specific approach, where the objectives behind water distribution could evolve as drought conditions intensify. The development of an Urban Drought Indicator as a result of these discussions exemplifies how stakeholder insights can be translated into practical tools for policymaking.

The optimization formulation developed in this research demonstrated how ethical discussions on fairness could be translated into numerical distribution policies. By enabling the exploration of different combinations of objectives, this formulation provides an effective means for navigating the trade-offs inherent to water distribution decisions. However, the analysis also revealed the limitations of the currently available data and highlighted the need for continuous improvement and further validation with stakeholders.

Finally, the DST proposed in this thesis emphasizes the value of continuous learning and knowledge co-creation in water management. Rather than prescribing a single policy, the Tool is designed to facilitate ongoing dialogue and adaptation among policymakers, ensuring that distribution policies remain responsive to evolving conditions and stakeholder needs. The DST design, which allows for the integration of new data and iterative improvements, reflects a forward-looking approach to governance that can accommodate the dynamic nature of Guadalajara's water supply system.

5.2 Limitations

A Decision Support Tool was developed that could guide decision-makers in selecting distribution policies based on justice-related objectives. To do so, a participatory and simulation-based methodology was developed and implemented. Although the objectives proposed for this project have been met, there are some key limitations that need to be discussed.

Data limitations and model simplicity

The data used to populate the GDL model is highly aggregated and simplified which could jeopardize the possibility of using this model to identify a useful operation policy. The spatial heterogeneity of some variables, such as loss in the water network, is not recognized. This limitation could be particularly relevant as such variables are also identified as highly sensitive in terms of water supply reliability (R-Cities, 2022). Differences in the water loss between the SAs could mean that distributions that are expected to distribute water, for example under an Egalitarian approach, might fail to do so in reality. As these differences are unknown, this limitation cannot be assessed. Additionally, the data used to populate the model was sourced in 2020 further increasing the inaccuracies and uncertainties. To tackle this limitation, the optimization framework was designed to be able to easily incorporate new data.

Finally, the way that the network is currently operated is based on the levels of water storage tanks distributed in the city. The current implementation of the model doesn't consider these water storage volumes and storage level states as inputs. This type of input data was represented in the model as the flow deficit indicator. However, it was disfavoured by participants of the workshop as it is difficult to implement. This mismatch between the indicators used by the water operators and the ones useful for the operation of the grid could further difficult the implementation of the project.

Workshop biases and shortcomings

The design and implementation of the participatory Workshop was one of the components of this project that most resources were invested in. This design resulted from a literature review of both the context of GDL and the scientific discussion that could inform the project. Additionally, an initial computational experimentation stage had already been conducted revealing the main inputs and discussion points that needed to take place during the workshop. Nonetheless, the lack of documented experiences in both formulation of MOO problems with the DJP using workshops and with this particular distribution problem resulted in mistakes that could have been avoided (Appendix 9). In particular, the line between a non-prescriptive and structured knowledge co-creation process was highly difficult to navigate. Even though participants were continuously encouraged to propose their own ideas, having resources available such as the DJP and a set of indicators could have forced convergence towards specific solutions. However, leaning further towards an unstructured workshop could have led to results that could not be implemented in the following Experimentation Stages, for example by using indicators that cannot be calculated with the GDL model.

All the participation goals of the workshop in terms of quantity, diversity and degree of influence of the participants were met. However, in the design of this workshop, it was decided that it would focus only on academia, civil society and decision-makers. Failing to incorporate a broader range of sectors, particularly water users from vulnerable communities, could incorporate biases and lead to overlooked problems and solutions. However, there were no resources available to broaden the scope of the workshop. To tackle this limitation, participants that could advocate for the interests of vulnerable social sectors, such as researchers and representatives from water authorities and spatial planning authorities, were invited. For an initial exploration stage, this representative approach to participation was considered to be sufficient.

Optimization framework

The proposed approach implies that an optimization will be made at each decision step. This approach enables high flexibility and could lead to finding optimal solutions more precisely than using approximators trained on a wide data set. However, this approach also implies a risk of producing sub-optimal solutions if the algorithm is unable to converge for any particular drought conditions. This risk was mitigated by conducting experiments for representative scenarios across the drought space and by having a precautionary approach while choosing hyper-parameters. The results of the experimentation stage do point out that the selected approach can be sufficient to find global maxima or close to global maxima solutions for the single objectives. However, these experiments were only conducted for three representative scenarios thus, there could be regions of the drought space that present artefacts that should be further studied. As the model is simple with no non-linearities, derivatives or any other complex calculation, it is considered that this approach is sufficient.

As discussed in Section 4.2, the analysis of the different problem formulations' capacity to provide desirable compromise solutions was inconclusive. This limitation can be detrimental as compromise policies might become the most used feature of the DST. Additional research is needed to explore how policies that optimize for more than one DJP or combinations of DJP with other objectives should be conducted.

Influencing GDL's decision-making

Considering the limitations mentioned above, particularly those related to the available data and model oversimplifications, it is unlikely and even not desirable that the distribution policies produced by the optimization algorithm can be directly implemented in the AqP. However, this doesn't mean that the research project and its results cannot influence decision-making in GDL.

First of all, in light of the feedback received after and during the workshop, it was clear that there was an interest in the methods and overall approach to decision-making that DMDU offers. As the workshop included high-level decision-makers, there could be an impact of this research project in GDL derived only from their participation in the workshop.

Secondly, developing distribution policies that could readily be implemented in the infrastructure was never an objective of this project. In contrast, this project aims at developing a Decision-Making Framework and a Tool that can be used to define what objectives could be used to distribute water in GDL under what conditions. In that sense, this research could be highly useful to guide subsequent participatory stages where decision-makers and potentially a broader range of actors could explore how MOO and the DJPs could be used to tackle this decision-making problem. The results of such a process will then be integrated into other computational exploration stages leading to its potential eventual implementation.

5.3 Flexibility, Knowledge Co-creation and Learning for DMDU

DMDU provides a structured way to navigate the complexities, uncertainties, and dynamic nature of real-world decision-making. By exploring possible current and future states of the world it can aid in ensuring that decisions remain effective in the face of deep uncertainty. Robustness is one of the main paradigms of DMDU in which a solution must be able to withstand multiple possible futures. This approach has been widely used for planning problems however, it has been used less for management problems where the decision timeframes are fast and iterative. Adaptive policies are plans that are laid out in a design stage but can take different paths or react to measurable changes in the system. This approach has been mainly designed and applied for planning and infrastructure sequencing (Zeff et al., 2016), but can also be applied to management problems such as speed control (Marchau et al., 2019), reservoir management (Marton & Knoppová, 2019; Sarva et al., 2021; Zatarain Salazar et al., 2022) and in problems bridging the two decision timeframes (Gold et al., 2023).

The decision-making problem presented in this thesis is an example of an infrastructure management problem characterized by deep uncertainty, particularly around values, and a high degree of novelty. The water distribution system of Guadalajara will evolve continuously. Some of these changes are the result of planning processes, such as the incorporation of a new SA mentioned in the workshop. Other changes are known unknowns, such the expected intensification of drought conditions due to climate change. While other changes are unpredictable or unknown unknowns. As the system evolves, so will the values and priorities of all the stakeholders that have any degree of influence in how the system is managed. Additionally, new opportunities to learn about the system and redefine the values around water distribution will arise after the implementation of any new policy. Adaptive Decision-Making could be useful to tackle such uncertain and evolving problems. However, it is necessary that any framework used for this case is flexible enough to accommodate these changes and incorporates learning via knowledge co-creation cycles. These mechanisms can ensure that the policy evolves together with the system, our understanding of it and the values around water distribution under drought.

Simple models, such as the GDL model are key to foster this type of learning and flexibility. This simplicity enables explainability and transparency that more complex models often fail to do so (Helgeson et al., 2021). Thus, these models can be used first as a boundary object between stakeholders with different backgrounds (Schwartz et al., 2018) to catalyse discussions resulting in knowledge co-production. By facilitating such inclusive collaborative decision-making processes the resulting policies can not only be more effective and fair, but also more easily adopted (Moallemi et al., 2023). After the policies are implemented, the same simple models can be used to communicate the policies and foster learning thus facilitating the continuous evolution of the policy.

The insights and tools generated in this research are designed, not as final solutions, but as one part of a continuous effort to learn how to live well in increasingly challenging conditions. As water becomes more scares, new challenges will continue to emerge. Having the tools to identify, learn from and adapt to those challenges is necessary to reduce the impacts of climate change as well as the other socioenvironmental challenges ahead despite uncertainty.

5.4 Towards Integrated Water Scarcity Management

Guadalajara, like many other cities in the world, faces and will continue to face water scarcity. As this condition continues to intensify, all elements of water governance, such as the instruments, institutions, stakeholders and tools will need to adapt. In order to move towards a more just distribution of water as water becomes scarcer, a water distribution framework with justice consideration, such as the one proposed in this thesis, will not be enough. A number of other innovative policies in the complete water management cycle will need to be developed, implemented and articulated with each other (**Figure 32**).

As the paradigms of water management have evolved together with our technologies and environment, a new one, where water scarcity is at the core, could emerge. Under this paradigm, drought is no longer seen as an anomaly or a failure of the system but rather as a characteristic. Thus, all the policies focused on water sourcing, distribution and use as well as watershed management should be designed considering recurrent and worsening scarcity.

This vision of a science-based Integrated Water Scarcity Management for Guadalajara with a justice approach was the final idea shared in the workshop. The path towards a modern approach of decision-making where drought is carefully prepared for considering and where tools that integrate every aspect of policy-making, from the ethical to the technical, are streamlined, is long. We hope that this project becomes part of that process.

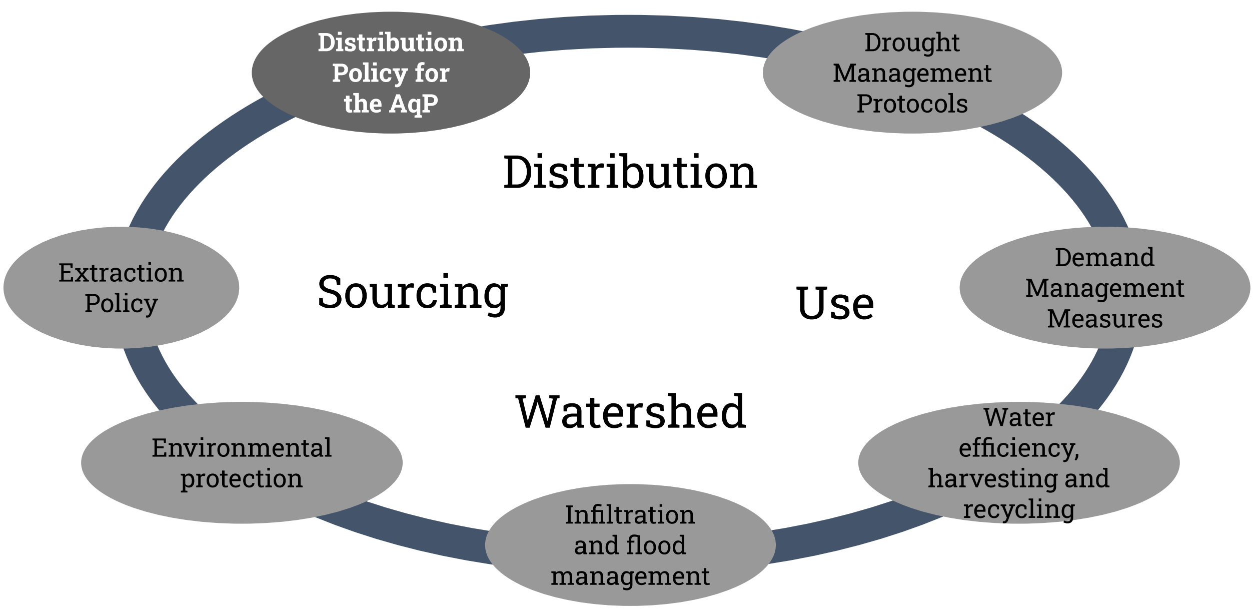


Figure 32. Complementary policies for the distribution policy for the AqP

5.5 Future Research

During this project, eight key areas of opportunity for improvement and future research with high scientific and societal value were identified.

Model improvement
The current implementation of the AMG model includes a large number of assumptions that carry out uncertainties. One of the most notorious ones is the lack of precise data at an SA level. Currently, leakage and demand per capita are assumed constant for the whole city. Additional water flows between potabilization plants have also been defined as constant due to a lack of data. In particular, the distribution of water between PP1 and PP2 and between PP1 and PP4 has not been yet characterized with sufficient precision. These flows could also be set as levers and included within the optimization.

Distributive Justice Principles formulation
Currently, the Egalitarian and Utilitarian DJPs are the most developed in the literature and thus the best-implemented ones in this research. Future works could further focus on a formalization of the Prioritarian principle with participatory weight assignment using qualitative quantitative methods. These works would be highly relevant as the Prioritarian principle was the second one most favoured during the workshop. Additionally, more exploration on combinations of objectives could be conducted, for example by incorporating the Sufficientarian objectives similar to the Truncated Utilitarian principle mentioned by (Doorn, 2019) where a high-performing utilitarian policy is found amongst the policies that ensure a minimum threshold for all.

Interactive Policy Evaluation workshop
Using the insights and tools generated in this research, a second participatory process should be conducted focused on validating the optimization framework and on defining an initial Distribution Policy for what objectives should be used under what conditions. This workshop would use the DST for just distribution policies or a future version of it.

Water supply reduction impact assessment
Due to the complex nature of the urban water distribution system, it is unclear what can be the impacts of a reduction in water supply in each SA. In particular, participants of the workshop mentioned that poorest neighbourhoods within each SA might be the most affected as they are often located in areas with higher altitude. Further analysis can be made to understand the spatial distribution of the impacts of a water supply deficit. This analysis could influence future formulations of distribution policies to limit the disproportionate impacts on marginalized communities.

Optimization implementation improvement
To ensure that the optimization algorithm converges, a precautionary approach was implemented where the nfes were set to 50,000 although it was observed that 40,000 was sufficient for convergence. On the other hand, this assessment was only made for a single scenario for the final problem formulation. Thus, it could be possible that some convergence issues are found in other areas of the uncertainty space. An alternative approach would be to incorporate a stopping mechanism that would ensure convergence more reliably (Martí et al., 2009). Additionally, the current optimization implementation uses a numerical precision that is not achievable with the infrastructure. A future implementation could use less significant digits to reduce computing time.

Improve Urban Drought Indicator

The current method to develop the Urban Drought Indicator was a logistic regression. This method provided very clear benefits as compared with PRIM, but had some inefficacies for the low and mid-drought conditions (**Figure 27**). These edge cases, that are currently observable as the risky cases defusing into the safe areas or vice versa in **Figure 27** should be further studied. Future works could assess other methods for scenario exploration such as CART (Bryant & Lempert, 2010) or Gradient Boosted Trees (Trindade et al., 2020). Additionally, other conceptual formulations of urban drought intensities via more extensive participatory processes could be explored.

A-priori a-posteriori assessment for compromise policies

DST proposes a compromise solution that balances the scores of the selected objectives. This compromise solution is likely to become the preferred one for any non-single objective formulation. However, the results of the analysis of the different problem formulations for finding optimal compromise solutions were highly inconclusive. Additionally, in this research, only one method for finding compromise solutions was implemented. Future works could further assess other methods for finding compromise solutions such as quantile-based satisfying criteria or participatory exploration of trade-offs (Kitayama & Yamazaki, 2012).

Explainability enhancement

The proposed approach for finding policies based on a set of objectives uses a Multi-Objective Evolutionary Algorithm (MOEA). This algorithm uses Artificial Intelligence (AI) methods to generate the Pareto Set of candidate solutions. By using AI, this approach can enable fast convergence towards optimal solutions, however, there’s a trade-off on explainability (Osika et al., 2023). Indeed, MOEAs are a black box method thus requiring policy-makers to trust in the algorithm’s results as it is not possible to trace how exactly were the solutions found. This lack of explainability can pose significant challenges for incorporating these methods into real decision contexts. Explainable AI is a growing research field as well as a growing concern for researchers, practitioners and decision-makers. Future works can leverage these tools to ensure that policymakers and other sectors accept the use of AI to inform critical decisions.

Integration with Reservoir Management Policies

In the current implementation of the optimization model, the water flows from the four sources are conceptualized as an uncertainty. However, the water authority can, most of the time, decide how much water to extract from each source. Future works could include water extraction as a lever and consider the storage of water in the reservoirs. This implementation could explore the trade-offs between justice and robustness by implementing measures that limit water flow in the short-term (thus generating a less fair distribution) to save water when drought conditions are expected to prolong (thus making more robust and resilient reservoir management).

References

Adler, M., Anthoff, D., Bosetti, V., Garner, G., Keller, K., & Treich, N. (2017). Priority for the worse-off and the social cost of carbon. *Nature Climate Change*, *7*(6), 443–449. https://doi.org/10.1038/nclimate3298

Afsar, B., Silvennoinen, J., & Miettinen, K. (2023). A Systematic Way of Structuring Real-World Multiobjective Optimization Problems. In M. Emmerich, A. Deutz, H. Wang, A. V. Kononova, B. Naujoks, K. Li, K. Miettinen, & I. Yevseyeva (Eds.), *Evolutionary Multi-Criterion Optimization* (Vol. 13970, pp. 593–605). Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-27250-9_42

Arnstein, S. R. (1969). A Ladder Of Citizen Participation. *Journal of the American Institute of Planners*, *35*(4), 216–224. https://doi.org/10.1080/01944366908977225

Ayo, A. (2022, November 13). *Governance of scarcity* [Personal communication].

Bryant, B. P., & Lempert, R. J. (2010). Thinking inside the box: A participatory, computer-assisted approach to scenario discovery. *Technological Forecasting and Social Change*, *77*(1), 34–49. https://doi.org/10.1016/j.techfore.2009.08.002

Ciullo, A., Kwakkel, J. H., De Bruijn, K. M., Doorn, N., & Klijn, F. (2020). Efficient or Fair? Operationalizing Ethical Principles in Flood Risk Management: A Case Study on the Dutch-German Rhine. *Risk Analysis*, *40*(9), 1844–1862. https://doi.org/10.1111/risa.13527

David Schlosberg. (2007). *Defining Environmental Justice: Theories, Movements, and Nature*. OUP Oxford. https://search.ebscohost.com/login.aspx?direct=true&db=nlebk&AN=215216&site=ehost-live&authtype=sso&custid=s1131660

Díaz-Vázquez, D., Camacho-Sandoval, T., Reynoso-Delgadillo, J., Gómez-Ayo, N. A., Macías-Calleja, M. G., Martínez-Barba, M. P., & Gradilla-Hernandez, M. S. (2023). Characterization and multicriteria prioritization of water scarcity in sensitive urban areas for the implementation of a rain harvesting program: A case study for water-scarcity mitigation. *Urban Climate*, *51*, 101670. https://doi.org/10.1016/j.uclim.2023.101670

Doorn, N. (2019). *Water Ethics: An Introduction*. https://rowman.com/ISBN/9781786609519/Water-Ethics-An-Introduction

Doorn, N. (2024). *Discussion on Distributive Justice Principles pertinence for Guadalajara's Aqupaheric* [Personal communication].

El Universal. (2024, May 9). *Fallas eléctricas afectan bombeo de agua desde Lago de Chapala a Guadalajara: Enrique Alfaro | El Universal*. https://www.eluniversal.com.mx/estados/fallas-electricas-afectan-bombeo-de-agua-desde-lago-de-chapala-a-guadalajara-enrique-alfaro/

Gold, D. F., Reed, P. M., Gorelick, D. E., & Characklis, G. W. (2023). Advancing Regional Water Supply Management and Infrastructure Investment Pathways That Are Equitable, Robust, Adaptive, and Cooperatively Stable. *Water Resources Research*, *59*(9), e2022WR033671. https://doi.org/10.1029/2022WR033671

Haasnoot, M., Kwakkel, J. H., Walker, W. E., & Ter Maat, J. (2013). Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world. *Global Environmental Change*, *23*(2), 485–498. https://doi.org/10.1016/j.gloenvcha.2012.12.006

Helgeson, C., Srikrishnan, V., Keller, K., & Tuana, N. (2021). Why Simpler Computer Simulation Models Can Be Epistemically Better for Informing Decisions. *Philosophy of Science*, *88*(2), 213–233. https://doi.org/10.1086/711501

IMEPLAN. (2020). *Programa de Accion Climática del Area Metropolitana de Guadalajara*.

IMEPLAN. (2023). *Estudio de Hidrología Subterránea en el Área Metropolitana d _Guadalajara*.

Kitayama, S., & Yamazaki, K. (2012). Compromise point incorporating trade-off ratio in multi-objective optimization. *Applied Soft Computing*, *12*(8), 1959–1964. https://doi.org/10.1016/j.asoc.2012.03.024

Kollat, J. B., & Reed, P. M. (2006). Comparing state-of-the-art evolutionary multi-objective algorithms for long-term groundwater monitoring design. *Advances in Water Resources*, *29*(6), 792–807. https://doi.org/10.1016/j.advwatres.2005.07.010

Kwakkel, J. H. (2019). A generalized many-objective optimization approach for scenario discovery. *FUTURES & FORESIGHT SCIENCE*, *1*(2), e8. https://doi.org/10.1002/ffo2.8

Lepri, B., Staiano, J., Sangokoya, D., Letouzé, E., & Oliver, N. (2017). The Tyranny of Data? The Bright and Dark Sides of Data-Driven Decision-Making for Social Good. In T. Cerquitelli, D. Quercia, & F. Pasquale (Eds.), *Transparent Data Mining for Big and Small Data* (Vol. 32, pp. 3–24). Springer International Publishing. https://doi.org/10.1007/978-3-319-54024-5_1

Marchau, V., Walker, Warren E, Bloemen, Pieter J. T. M., & Popper, Steven W. (2019). *Decision Making under Deep Uncertainty*. https://library.oapen.org/handle/20.500.12657/22900

Martí, L., Garcia, J., Berlanga, A., & Molina, J. (2009). An Approach to Stopping Criteria for Multi-objective Optimization Evolutionary Algorithms: The MGBM Criterion. In *2009 IEEE Congress on Evolutionary Computation, CEC 2009* (p. 1270). https://doi.org/10.1109/CEC.2009.4983090

Marton, D., & Knoppová, K. (2019). Developing hydrological and reservoir models under deep uncertainty of climate change: Robustness of water supply reservoir. *Water Supply*, *19*(8), 2222–2230. https://doi.org/10.2166/ws.2019.102

Moallemi, E. A., Kwakkel, J., De Haan, F. J., & Bryan, B. A. (2020). Exploratory modeling for analyzing coupled human-natural systems under uncertainty. *Global Environmental Change*, *65*, 102186. https://doi.org/10.1016/j.gloenvcha.2020.102186

Moallemi, E. A., Zare, F., Hebinck, A., Szetey, K., Molina-Perez, E., Zyngier, R. L., Hadjikakou, M., Kwakkel, J., Haasnoot, M., Miller, K. K., Groves, D. G., Leith, P., & Bryan, B. A. (2023). Knowledge co-production for decision-making in human-natural systems under uncertainty. *Global Environmental Change*, *82*, 102727. https://doi.org/10.1016/j.gloenvcha.2023.102727

Muller, J. Z. (2018). *The tyranny of metrics*. Princeton University Press.

Murphy, C., & Gardoni, P. (2008). The Acceptability and the Tolerability of Societal Risks: A Capabilities-based Approach. *Science and Engineering Ethics*, *14*(1), 77–92. https://doi.org/10.1007/s11948-007-9031-8

Norström, A. V., Cvitanovic, C., Löf, M. F., West, S., Wyborn, C., Balvanera, P., Bednarek, A. T., Bennett, E. M., Biggs, R., De Bremond, A., Campbell, B. M., Canadell, J. G., Carpenter, S. R., Folke, C., Fulton, E. A., Gaffney, O., Gelcich, S., Jouffray, J.-B., Leach, M., … Österblom, H. (2020). Principles for knowledge co-production in sustainability research. *Nature Sustainability*, *3*(3), 182–190. https://doi.org/10.1038/s41893-019-0448-2

Nyahora, P. P., Babel, M. S., Ferras, D., & Emen, A. (2020). Multi-objective optimization for improving equity and reliability in intermittent water supply systems. *WATER SUPPLY*, *20*(5), 1592–1603. https://doi.org/10.2166/ws.2020.066

Popper, S. W. (2019). Robust decision making and scenario discovery in the absence of formal models. *FUTURES & FORESIGHT SCIENCE*, *1*(3–4), e22. https://doi.org/10.1002/ffo2.22

Popper, S. W., Molina-Perez, E., Groves, D. G., Ramirez, A. I., & Crespo-Elizondo, R. (2019). *Developing a Robust Water Strategy for Monterrey, Mexico: Diversification and Adaptation for Coping with Climate, Economic, and Technological Uncertainties*. https://policycommons.net/artifacts/4835882/developing-a-robust-water-strategy-for-monterrey-mexico/5672599/

Quinn, J. D., Reed, P. M., Giuliani, M., Castelletti, A., Oyler, J. W., & Nicholas, R. E. (2018). Exploring How Changing Monsoonal Dynamics and Human Pressures Challenge Multireservoir Management for Flood Protection, Hydropower Production, and Agricultural Water Supply. *Water Resources Research*, *54*(7), 4638–4662. https://doi.org/10.1029/2018WR022743

Ramani, K., Rudraswamy, G. K., & Umamahesh, N. V. (2023). Optimal Design of Intermittent Water Distribution Network Considering Network Resilience and Equity in Water Supply. *WATER*, *15*(18), 3265. https://doi.org/10.3390/w15183265

R-Cities. (2022). *Agenda de Resiliencia Hídrica del Area Metropolitana de Guadalajara*.

Rimon, F. (2023). *Exploring distributive justice in water resource allocation*.

Rooney-Varga, J. N., Sterman, J. D., Fracassi, E., Franck, T., Kapmeier, F., Kurker, V., Johnston, E., Jones, A. P., & Rath, K. (2018). Combining role-play with interactive simulation to motivate informed climate action: Evidence from the World Climate simulation. *PLOS ONE*, *13*(8), e0202877. https://doi.org/10.1371/journal.pone.0202877

Sarva, S., Kwakkel, J., Zatarain Salazar, J., & Doorn, N. (2021). *Operationalising stability and fairness in transboundary water resource allocations*. https://repository.tudelft.nl/islandora/object/uuid%3A683a47b3-89fd-4ebf-8ba6-1a2fe6c15b65

Schwartz, M. W., Cook, C. N., Pressey, R. L., Pullin, A. S., Runge, M. C., Salafsky, N., Sutherland, W. J., & Williamson, M. A. (2018). Decision Support Frameworks and Tools for Conservation. *Conservation Letters*, *11*(2), e12385. https://doi.org/10.1111/conl.12385

Shavazipour, B., Kwakkel, J. H., & Miettinen, K. (2021). Multi-scenario multi-objective robust optimization under deep uncertainty: A posteriori approach. *Environmental Modelling & Software*, *144*, 105134. https://doi.org/10.1016/j.envsoft.2021.105134

SIAPA. (2014). *Plan Institucional*.

Trindade, B. C., Gold, D. F., Reed, P. M., Zeff, H. B., & Characklis, G. W. (2020). Water pathways: An open source stochastic simulation system for integrated water supply portfolio management and infrastructure investment planning. *Environmental Modelling & Software*, *132*, 104772. https://doi.org/10.1016/j.envsoft.2020.104772

Trindade, B. C., Reed, P. M., Herman, J. D., Zeff, H. B., & Characklis, G. W. (2017). Reducing regional drought vulnerabilities and multi-city robustness conflicts using many-objective optimization under deep uncertainty. *Advances in Water Resources*, *104*, 195–209. https://doi.org/10.1016/j.advwatres.2017.03.023

Valipour, R., & Ketabchi, H. (2023). *Equity, Social Welfare, and Economic Benefit Efficiency in the Optimal Allocation of Coastal Groundwater Resources-Web of Science Core Collection*. https://www-webofscience-com.tudelft.idm.oclc.org/wos/woscc/full-record/WOS:000952158200001

Xinying Chen, V., & Hooker, J. N. (2023). A guide to formulating fairness in an optimization model. *Annals of Operations Research*, *326*(1), 581–619. https://doi.org/10.1007/s10479-023-05264-y

Yang, G., Giuliani, M., & Castelletti, A. (2023). Operationalizing equity in multipurpose water systems. *HYDROLOGY AND EARTH SYSTEM SCIENCES*, *27*(1), 69–81. https://doi.org/10.5194/hess-27-69-2023

Zatarain Salazar, J., Kwakkel, J., & Witvliet, M. (2022). *Exploring global approximators for multiobjective reservoir control*. *55*(33), 34–41. https://doi.org/10.1016/j.ifacol.2022.11.006

Zeff, H. B., Herman, J. D., Reed, P. M., & Characklis, G. W. (2016). Cooperative drought adaptation: Integrating infrastructure development, conservation, and water transfers into adaptive policy pathways. *Water Resources Research*, *52*(9), 7327–7346. https://doi.org/10.1002/2016WR018771

Znabei, M. (2023). *Exploring Distributive Justice In Many-Objective Optimization: A Comparative Analysis of A Priori and A Posteriori Approaches to Implementing Distributive Justice Principles*.

Appendix 1. Literature Review Methodology

2.1 Approach

These queries were conducted in Web of Science (WoS) between January and February 2024 as part of the initial part of the research project.

Topics	WoS query	Articles found	Comments
Drought management using **DMDU** with **justice** considerations	(TS=(justice OR equity OR fairness OR fair)) AND (TS=("drought" OR "water scarcity")) AND (TS=("decision making under deep uncertainty" OR dmdu OR "robust decision making" OR "adaptive management" OR "adaptive planning"))	Total: 5 After screening: 1	The other publications were not actualy DMDU. The only publication found in this intersection is Gold et al. (2024). Upon reassessment of this query an additional publication was found from March 2024 but was not included.
DMDU and **drought**	(ALL=(("deep uncertainty" OR "deeply uncertain") AND (drought OR "water scarcity"))) NOT TI=(agriculture OR food OR mining)	Total: 35 After screening: 15	Publications focused on agriculture, mining or food security were excluded from the query and further excluded during screening.
Applications of **multi objective optimization** for **water supply** with **justice considerations**	(ALL = ((justice OR equit* OR fair*) AND (("multi-objective optimization") OR ("multiobjective optimization")) AND ("water supply" OR "supply of water" OR "Water allocation"))) NOT AB=(basin OR watershed)	Total: 21 After screening: 7	Broadened from drought to water supply but focused on MOO. Some results that focused primarily on agriculture, energy or wastewater, as well as on methods outside the scope of this research such as Agent Based modelling or Game Theory were screened out.
Applications of **DMDU** in **Mexico**	ALL = ((ALL=("deep uncertainty")) AND ALL=(Mexico)) NOT ALL=("New Mexico")	Total: 6 After screening: 4	Projects not in Mexico or not DMDU were screened out.
Participatory methods in **MOO**	(TS=("participatory process" OR "participatory approach" OR workshop OR "stakeholder engagement" OR co-creation OR "collaborative process") AND TS=("multi-objective optimization" OR "multiobjective optimization" OR "many-objective optimization")	Total: 60 After screening by WoS category: 17 After manual screening:	A large number of publications (50) on the topic relate to scheduling issues thus it was exlpuded in the query. Publications with a WoS category of physical sciences (physics, chemistry, biology, etc) and hard engineering (mechanics, manufacturing, electric) were excluded

	ANDDT=(article OR conference paper)) NOT TS=(schedul*)		

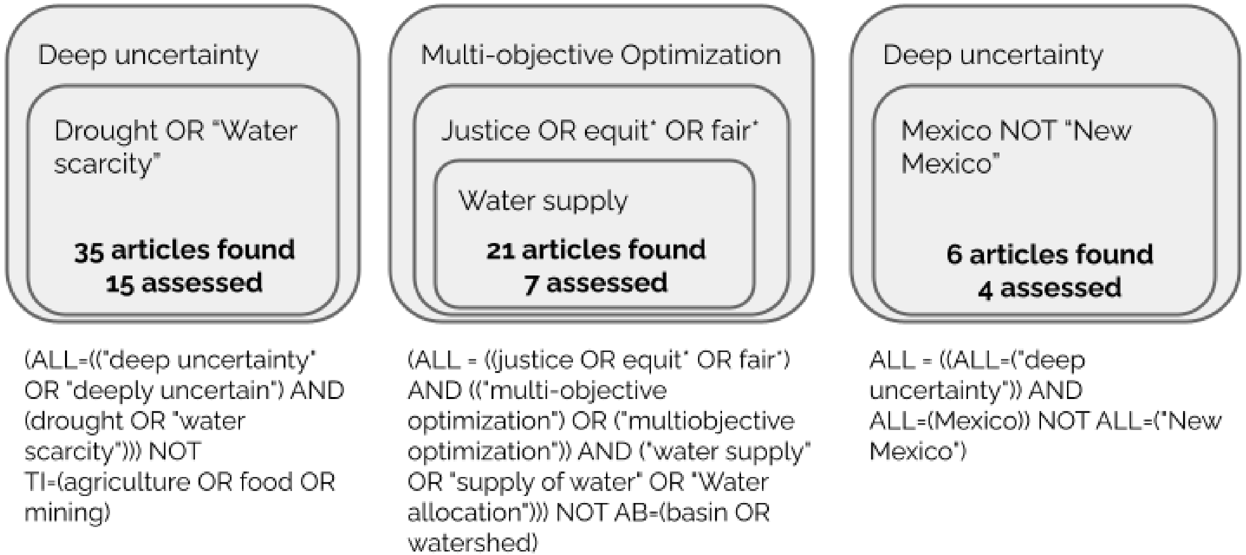


Figure 33. Literature review Web-of-Science queries

Appendix 2. Data

This data is summarized from the Technichal Report of the Interactive Decision Support Tool (R-Cities, 2022) available in https://public.tableau.com/app/profile/resiliencia.h.drica.amg/viz/HerramientadeResilienciaHdrica-AMGV12_4/Landing

Variable	Description	Timescal e	Baseline value	Source	Uncertainties
Households [units per SA]	Amount of water intake for domestic use supplied by the central water authority.	2020	SA_1=48,064 SA_1=8,051 SA_1=14,887 SA_1=9,412 SA_1=11,910	Estimated by R-Cities (2022) by intersecting a shapefile of supply areas and smaller administrative areas called Patronato that includes the amount of .	• Patronato shape file was assumed homogenously distributed. • A water intake could be used for more or less than a single household.
Average consumption [l/day/intake]	Average daily consumption per domestic intake.	2020-2021 Excluding	Domestic: 129 Commercial: 558 Public: 6,272 Industrial: 4,457	Estimated by R-Cities (2022) using the total amount of domestic intakes and total volume sold per month reported by SIAPA (2022) averaged for the non-anomalous months of 2020 and 2021.	• Data is not representative as only two years were used and they include COVID-related anomalies • Approximately 15% of the intakes don't have water meters and the consumption is assumed fixed and homogeneous. • There have been reports of altered or malfunctioning water meters as well as theft

Variable	Description	Timescale	Baseline value	Source	Uncertainties
Maximum extraction [m³/s]	Maximum flow that the water authority is legally allowed to extract from each water source.	Last updated in 2011	Chapala= 8.2 Calderon= 1.5 Toluquilla=1 Pozos=3.5	SIAPA (2013)	● Extraction from superficial sources is closely monitored, however as underground extraction is mostly decentralized, the actual flow are uncertain.
Potabilization leakage [%]	Proportion of water extracted that is lost in potabilization plants.	2020-2021	8%	Estimated by R-Cities (2022) by averaging the monthly ratio between total output of the potabilization plants and the total extraction.	● The heterogeneity of the efficiency of the potabilization plants due to their diferent processes and technologies is not accounted for.
Grid leakage [%]	Proportion of water delivered by the potabilization plants and wells that is lost in the city's distribution grid.	2020-2021	35%	Estimated by R-Cities (2022) by averaging the monthly ratio between total volume sold for all uses and the output of potabilization plants and well extraction	● As this value is calculated using the volume of water sold it inherits its uncertainties. ● The heterogeneity in the efficiency of the infrastructure in the city is not accounted for. ● Well extraction is not precisely monitored.
Additional flows [%]	Proportion of water from some sources that flow to other SAs due to interconnections or the distributed well system	2020-2021	20% of Pozos flow towards PP3 12% of PP1 flow towards Toluquilla 2% of Pozos flow towards Toluquilla	Estimated by R-Cities (2022)	● These values resulted from a numerical calibration process due to a lack of data on water transfers and the flows of the distributed wells system thus it carries out high uncertainty.

Appendix 3. Scenario Exploration Tool Information layer

Name of Element	Type of Element	Description	Original data source
Guadalajara-Chapala Aqueduct	Conduction Line	The Chapala-Guadalajara Aqueduct is the most important distribution line in GDL with a design capacity of 7.5 m3/s, a total distance of 42.6 km, and a diameter of 2.1 m. It is estimated that it has an average flow of 5.3 m/s, which is channeled to PP1 and PP2 with an approximate proportion of 75/25. Various projects have been proposed to build a more efficient new aqueduct that increases the closed-conduit capacity of Chapala.	DIP (SIAPA, 2014)
Calderón System Aqueduct	Conduction Line	The Calderón System Aqueduct has a total distance of 31 km, a diameter of 1.83 m, and a design capacity of 3 m3/s. The average flow between 2017 and 2021 is 1.1 m3/s, with a maximum of 1.6 m3/s in April 2018.	DIP (SIAPA, 2014)
Santiago-Atequiza-Las Pintas System	Conduction Line	"The Santiago-Atequiza-Las Pintas system, also known as the old system, is the first mechanism to transport water from Chapala to GDL. The system starts at the Ocotán gate, regulating the flow from Chapala to the Santiago River, which later also receives the Zula River's inflow until it reaches the Corona Dam, where part of the flow is channeled to the Atequiza Canal, which then becomes the Las Pintas Canal and reaches PP1. The system's maximum capacity could exceed 9 m3/s. Being an open canal, it is the only conduction line that presents losses due to evaporation and infiltration, illegal connections, and agricultural users, averaging 4% of the water that passes through it or 3% of the water flowing through the four conduction lines, equivalent to 8.8 Mm3/year. Additionally, it receives considerable pollution flows from illegal drains and agricultural runoff, contributing to the high cost and volume of losses in the treatment of this flow."	DIP (SIAPA, 2014)
El Salto-La Red Aqueduct	Conduction Line	The La Red-Calderón Transfer project involves a conduction volume of 2 m3/s from the Verde River, which is channeled to the Calderón Dam.	DIP (SIAPA, 2014)
No. 1 "Miravalle"	Potabilization Plant	PP1 Miravalle, "Ing. Adol Guzmán Méndez," was built in 1956, receiving water from the Chapala Aqueduct and the old system. It has an installed capacity of 9 m3/s, with the highest monthly average inflow reaching 6.3 m3/s, representing 67% of installed capacity. This PP presents an average loss volume of 4.3% in the purification process.	Monthly inflow and outflow data from SIAPA, (2022) and DIP (SIAPA, 2014)
No. 2 "Las Huertas"	Potabilization Plant	PP2 - Las Huertas "C. David Gutiérrez Carvajal," built in 1991, receives water from Chapala through the Aqueduct and has an installed capacity of 2 m3/s. The maximum	Monthly inflow and outflow data from

Name of Element	Type of Element	Description	Original data source
		monthly average inflow is 1.9 m3/s, representing 93% of its installed capacity. It has an average loss volume of 3.7%. The land it occupies is available for future expansions.	SIAPA, (2022) and DIP (SIAPA, 2014)
No. 3 "San Gaspar"	Potabilization Plant	Potable Water Plant No. 3 San Gaspar, "Ing. Luis Basich Leija," built in 1991, receives water from the Calderón Dam and has an installed capacity of 2.3 m3/s. It has generated an average outflow of 1.0 m3/s between 2017 and 2021. The highest monthly average outflow it has reached is 1.5 m3/s in June 2020, representing 65% of its installed capacity. This PP presents an average loss of 3.5% in the purification process.	Monthly inflow and outflow data from SIAPA, (2022) and DIP (SIAPA, 2014)
No. 4 "Toluquilla"	Potabilization Plant	Potable Water Plant No. 4 Toluquilla, built in 2008, treats water extracted from the Toluquilla deep well system, which contains high levels of arsenic, manganese, and iron. It uses an advanced purification process with chlorine and ozone. It has an installed capacity of 1 m3/s, and between 2017 and 2021, it has had an average outflow of 0.5 m3/s and a maximum monthly outflow of 0.7 m3/s. Due to the type of purification process, this PP does not present losses. There are projects to add a hardness module and expand the plant's capacity, although a larger extracted volume is needed. Currently, this PP is the only one operated by a private entity.	Monthly inflow and outflow data from SIAPA, (2022) and DIP (SIAPA, 2014)
PP1 - Chapala	Supply Zone	This zone is supplied by PP1 - Miravalle, which is fed by Chapala and is the most populated zone in GDL. Most of its population (59%) has a low or very low level of marginalization. Although only 13% of its population has a high or very high level of marginalization, being the most populated zone, it is also the area with the most marginalized population and the highest percentage of very high marginalization (1.8%). Currently, it has 371 rainfall capture systems serving these populations.	Census 2020 (INEGI), SGIA (2022), SIAPA (2022)
PP2 - Chapala	Supply Zone	This zone is supplied by PP2 - Las Huertas, which is fed by Chapala through the Aqueduct. 60% of its population has a medium level of marginalization and presents the lowest proportion of population with low and very low marginalization (30%). 10% of its population has high and very high levels of marginalization, so 358 rainfall capture systems have been installed in those areas.	Census 2020 (INEGI), SGIA (2022), SIAPA (2022)
PP3 - Calderón - Colomos	Supply Zone	"This zone is supplied by PP3, which treats water from Calderón. 59% of its population has a low or very low level of marginalization. Additionally, it is the zone with the highest proportion of population with high or very high marginalization (17%), so more than 1,548 rainfall capture systems have been installed to serve the most vulnerable populations affected by the 2021 water crisis. This zone also has a supply of underground sources, such as the Colomos Spring and some wells with an estimated flow of 0.5 m3/s under normal conditions."	Census 2020 (INEGI), SGIA (2022), SIAPA (2022)

Name of Element	Type of Element	Description	Original data source
PP4 - Toluquilla	Supply Zone	This zone is supplied by all the water from PP4, fed by the Toluquilla well system, and has a flow from PP1 of 0.6 m3/s. This is the zone with the highest proportion of the population with a low or very low level of marginalization (70%) and the lowest proportion of the population (9%) with high or very high marginalization. It has 442 rainfall capture systems installed in areas of high to very high marginalization.	Census 2020 (INEGI), SGIA (2022), SIAPA (2022)
Pozos Well System	Supply Zone	This is the second most populated zone in GDL. It is supplied by isolated wells, well systems such as Tesistán and Bajío la Arena, and springs that receive chlorination and are injected into the supply network. The water is mainly extracted from the Tesistán aquifer, which has been considered overexploited since 2004. This zone has the second lowest proportion of the population with a very low or low level of marginalization (69%) but the second highest proportion of the population with a high or very high level of marginalization (15%). Despite having a large marginalized population, no rainfall capture systems have been installed in this zone in the initial stages of the project because it relies entirely on underground sources, and no water scarcity situations have been reported.	Census 2020 (INEGI), SGIA (2022), SINA (CONAGUA, 2022), SIAPA (2022)
El Ahogado Water Reuse Plant	Treatment Plant	With the Purple Line project, this plant is expected to generate 0.5 m3/s of water for industrial use. Additionally, there are proposals for this plant to generate 2.5 m3/s for public urban use, which will be supplied to PP1 and PP2.	the proposal presented by the Governor of the State of Jalisco in 2022.
Urban Distribution Network	Unaccounted Water	The urban distribution network of GDL operated by SIAPA has more than 8.5 thousand linear kilometers, 87% of which are over 30 years old, and 65% are made of cement or asbestos. In 2020, the unaccounted water in GDL urban network was estimated at 35% of the supplied water, according to SIAPA data (2022).	SIAPA (2022)
Santiago River	Water Body	The Santiago River is the second longest in the country, stretching 475 km from Chapala to the Pacific Ocean. Due to domestic, industrial, and agricultural discharges, the river has high levels of pollution. In recent years, the "Let's Revive the Santiago River" project has started, aiming to monitor water quality, reduce pollution sources, and clean the river to improve the quality of life of people living nearby and ensure ecological integrity with an environmental health perspective.	https://riosantiago.jalisco.gob.mx/estrategia
Zula River	Water Body	The Zula River, with an extension of 131 km, flows into the Santiago River near its origin in the municipality of Ocotlán. Due to agricultural and urban discharges, it contains a significant load of pollutants contributing to the Santiago River's problems.	SINA CONAGUA (2022)

Name of Element	Type of Element	Description	Original data source
Verde River	Water Body	The Verde River originates in the Verde River basin in the Altos de Jalisco. The CEA has an extraction concession volume for GDL of 5.6 m3/s in the municipality of Zapotlanejo. However, the only current extraction project for this water body for GDL is the El Purgatorio - El Salto - La Red - Calderón transfer, which is expected to contribute 2 m3/s to the Calderón Dam.	http://www.aguas.org.mx/sitio/blog/noticias/item/520-otorgan-concesion-para-aprovechar-el-rio-verde-en-jalisco.html
Chapala Lake	Water Source	"Chapala Lake is the largest lake in the country and the main water source for GDL (SIAPA, 2022). It has a variable storage volume between 3,000 Mm3 and 6,500 Mm3. Its main inflow is the Lerma River, originating in the Valley of Toluca in the State of Mexico. The reference value for extraction from Chapala is 6.9 m3/s, equivalent to the 2020 extraction considering the linear increasing trend between 2002 and 2021. The maximum monthly average is 8.2 m3/s, and the minimum is 5.9 m3/s. Currently, the extraction flow from Chapala for GDL is limited by the Distribution Agreement to an annual average of 7.6 m3/s."	SIAPA (2022)
Calderón Dam	Water Source	"The Calderón Dam has a capacity of 3 m3/s; however, the maximum volume it has supplied is 1.6 m3/s in April 2018. On the other hand, due to the drought that impacted the region between March 2020 and August 2021, the Calderón Dam reached the siltation level, and extraction had to be completely cut off between April and July 2021. With the Transfer project, the dam is expected to reach the 3 m3/s supply it is designed for."	SIAPA (2022)
Zapotillo	Water Source	Also known as the Transfer - El Salto - La Red - Calderón project, it aims to incorporate a new surface water source into GDL network by utilizing existing extraction concessions from the Verde River. It is proposed as a set of aqueducts that leverage existing dams to contribute an estimated average of 2 m3/s to the Calderón Dam. It is expected to be completed in 2024.	SIAPA (2022)

Note. Translated from Spanish to English using Chat GPT 4o and reviewed by the author.

Appendix 4. Facilitation Guide

Note. This is an unchanged version of the facilitation guide that was printed and supplied to each facilitator and volunteer.

Activity 1

The main goal of this activity is to go through all the relevant discussions to design an operation policy. By doing so, the participants will understand the complexity of the decision-making problem and the need for tools to tackle it. Additionally, the basic elements to start building a distribution policy in Activity 2 will be identified. Achieving consensus on the exact values of the Acuaferic is not a-priority. Rather starting a discussion on what should be the logic behind the distribution of water by going through the topics in the Printed material.

Activity questions and tasks

1. Display the the tool on the board, explore it and make sure that everyone has access to it.
2. Ask them to select the scenario "Sequía histórica", propose a solution and share it with others.
3. Point out to the indicators available to make the decisions and explain them and their nuances if necessary.
4. If there's consensus, start challenging them with triggering questions (Section 1.2)
5. While they discuss, start adding post-its with the ideas they mention about the indicators (red: missing, green: available), objectives, considerations, restrictions and adaptive considerations if they are mentioned. In the end, these post-its should reflect the logic behind their agreed-upon distribution proposal.
6. If the discussion stalls, guide the conversation towards the post-its you've already laid down and ask them if there's anything to add or remove or by relating it to triggering questions. (if any post-its are removed because they no longer represent their proposal, pass them to your co-facilitator.)
7. Once they've reached a consensus, write down the flows for each segment in (1)
8. *Ask them about how the logic behind their proposal might change if drought intensity increases and take notes (2). If possible you could ask them to select and try to solve Scenario RCP8.5 in the Scenario tool.*

Triggering topics & questions

- Indicators (strengths, weaknesses and improvement opportunities)
    - What are the upsides and downsides of basing your distribution proposal on the performance indicator X?
    - Should we include the demand for industry, public and services in those indicators?
- Differences in conditions of SA (vulnerability, density, criticality, etc)
    - There are some SA, like SA3 that have more vulnerabilities, should that affect water distribution?

- If there's more people living in SA1, should that affect water distribution?
- Is there an area where water supply is more critical than others for the well-being of the city?

- Differences in behaviours of SA (consumption per capita, access to water trucks)
  - How should we deal with the differences in consumption per capita between the SA?
- Distribution types (challenges of equity, and prioritization)
  - Equitable distribution
    - Does that indicator really reflect equity? Is there a better one?
    - How would you deal with the SA you're taking water from?
    - Does equity always make sense, even if there are intrinsic inequalities?
  - Heterogeneous distribution
    - Why are you prioritizing supply to SAx over SAy?
    - Why did you select indicator X to guide that prioritization?
- Limitations (viability of proposals)
  - Could someone oppose your distribution proposal?
- Uncertainties & assumptions
  - Are there some uncertainties that are critical for the success of the distribution policy?
  - Who are the winners and losers of your proposed distribution?
  - What conditions could make your assumptions fail?

Activity 2

Tasks

1. Present all the facilitation material and explain how they can build objectives using the cards and stickers.
2. Start by re-discussing the points mentioned in the introduction where there was the most consensus and offer to write down a first "low hanging" objective and add it to (1)
3. Ask them what other objectives could be necessary. You can use triggering questions about drought intensity or justice to further fuel the discussion.
4. In case no more objectives are being proposed try to ask questions to point out at how a single objective policy might fail, for example with a more intense drought.
5. If they propose restrictions (considerations that the policy HAS to comply with) that are not yet on the board, add them to (2)
6. As more objectives are proposed, start laying them in (1)
7. Once you have a set of objectives ask them to organize and prioritize them to make sure there's max 4. Ask them how these objectives relate to each other and which ones are compatible or not.
8. Build your final set of objectives (1)

Justice principles Triggering questions

- Utilitarian
  - Why are the differences between the SA not considered?
- Sufficientarian
  - How should we assign the resources between the SA that are above the threshold?
  - Is it the same if SAx or SAy are under the threshold? Are there some SA that we want to keep above the threshold over others?
- Egalitarian
  - Are we sure that indicator x enables an Egalitarian distribution? Why did you choose it over another? What if we have wrong assumptions about key uncertainties?
  - If some SA have more access to emergent measures such as water trucks, shouldn't we prioritize others?
- Prioritarianism
  - Is the selected indicator the best to guide the Prioritarian approach you propose?
  - How would you choose how much water to allocate to this priority area?

Appendix 5. Stakeholder Involvement Strategy

Representatives from the Government were involved thanks to the support of a local champion who had already worked with the author of this thesis. This champion facilitated the endorsement of this project by the directors of the State Water, thus triggering a snowball effect that resulted in high-level governmental participation from all the relevant institutions such as the Distribution Directorate of the State Water Commission and the Water Utility, the Coordination of Integral Water Management, the Coordination of Integral Territorial Management and the Directorate of Innovation of the State.

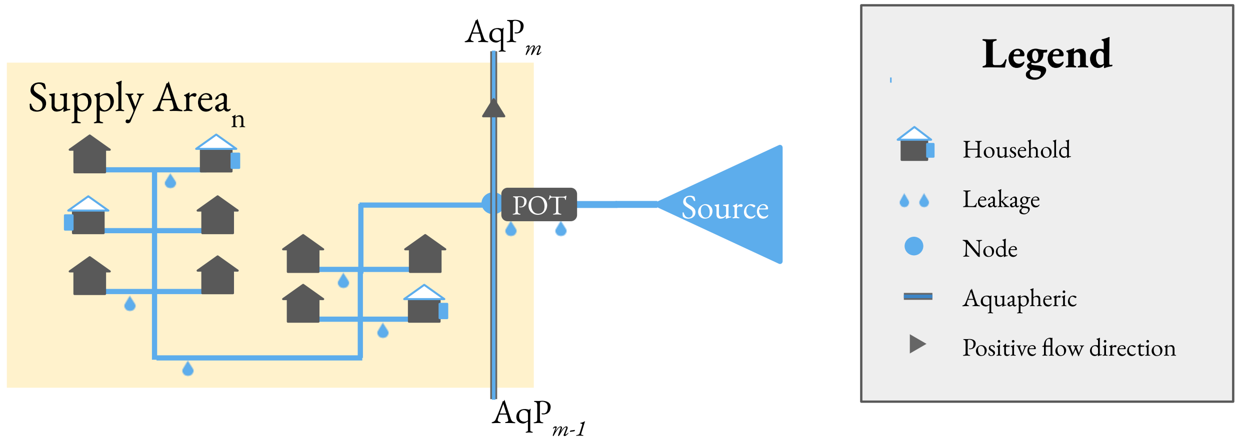
The Tec de Monterrey handled invitations for academic representatives through the Centre for the Future of Cities, the institution that funded the travels for the workshop and the Decision Science Laboratory from the School of Government which also funded part of the workshop expenses. The academic staff invited included researchers focused on urban planning, architecture, civil engineering, human rights law and sustainability. Representatives of the World Bank that previously collaborated with the School of Governments were invited as part of non-governmental organizations.

Appendix 6. Workshop Technichal Support Sheet

Technical Sheet

AMG Distribution Model

This model was developed by the Resilient Cities Network and Ithaca Environmental with the support of IMEPLAN, SGIA, and SIAPA in 2022 as part of the AMG Water Resilience Agenda (Figure 1). It is a decision-making model, not an operational network model. Therefore, it does not take into account accumulations and is based on flow values that can represent daily, monthly, or annual averages. It is a simple flow balance model in which supply (Eq. 1) and demand (Eq. 2) are calculated for each Supply Zone (SA), and with these two values, performance metrics such as the proportion of demand supplied (Eq. 3) are calculated.



Demand Calculation

Demand is calculated based on the number of connections for each use in the SA and the average demand for each use across the entire AMG. Average values were estimated using billing data from 2020 and 2021, excluding three months considered anomalous due to the pandemic.

- (Eq1) $Demand_n$ = Domestic intakes * Average domestic demand + Services intakes * Average services demand + Public intakes * Average public demand + Industrial intakes * Average industrial demand

Water Supply Calculation

The water supply to each SA was calculated considering the extraction associated with each source, minus losses in treatment, minus imports and exports of water between treatment plants, and losses in the network.

- (Eq. 2) $Supply_n$ = ($Source_n$ * (1 - Treatment losses) + $Imports_{n-1}$ - $Exports_n$) * (1 - Network losses)

Performance Indicator

The main performance indicator calculated by the model is the demand supplied. A value of 100% represents a situation where all demand is met. Due to the way the model is defined, it is possible to obtain values above 100%, meaning that more water is supplied than is theoretically necessary.

- (Eq. 3) Demand Supplied = $Supply_n$ / $Demand_n$

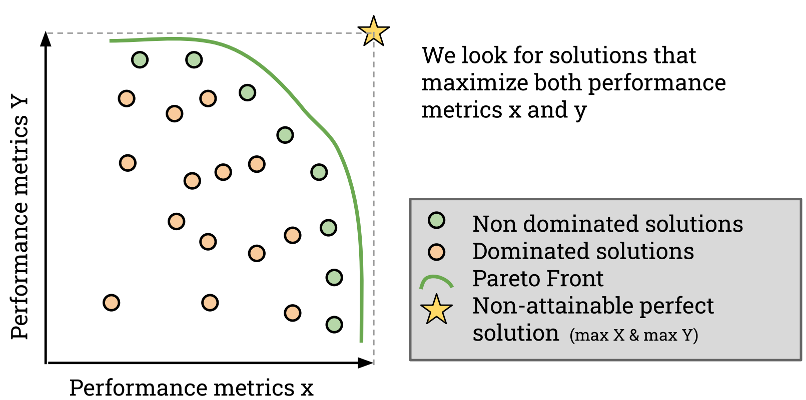
For more information, see: IMEPLAN Water Resilience Agenda

Mathematical Definition of a Distribution Policy

For this research, a distribution policy is defined as a set of equations that calculate the flow of water that should flow through each segment of the aqueduct based on the flows extracted from each source. Due to the nature of the problem, Radial Basis Functions (RBF), a type of artificial intelligence method that allows approximating nonlinear functions, were selected (Zatarain-Salazar, 2022).

Multi-Objective Optimization

Multi-objective optimization is a method for finding a set of optimal solutions to a problem with more than one performance metric. These performance metrics are often related, meaning that when actions are implemented to improve one, at least one other worsens. Therefore, there are no perfect solutions where the highest value can be reached for all metrics. Instead, optimal solutions are defined by the Pareto Front, which is the set of solutions where if any parameter is modified, the value for at least one performance metric would worsen. These solutions are called non-dominated or optimal solutions, and once identified, some method is required to select the most useful ones to address the problem.



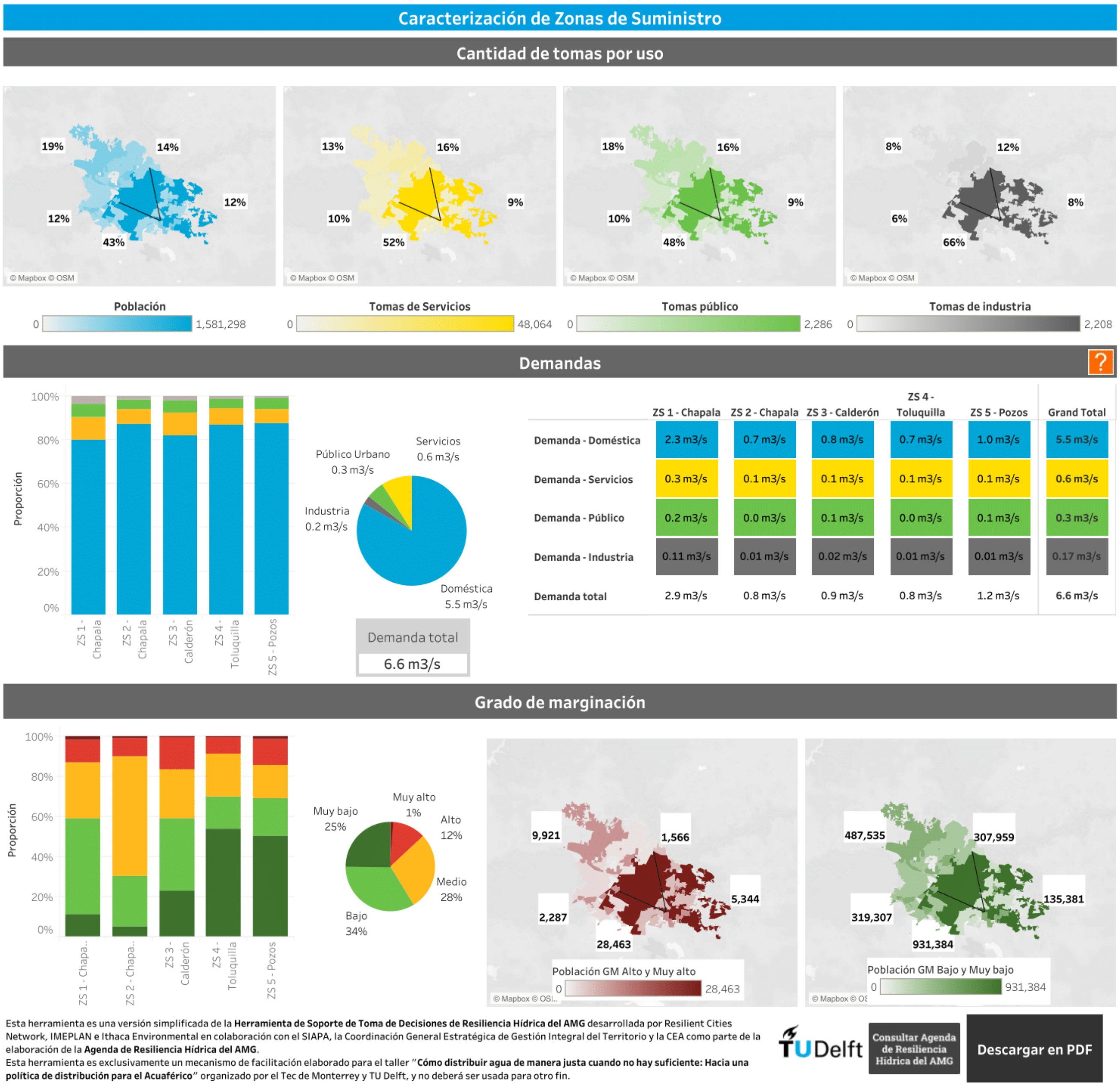
To find the set of optimal solutions, Multi-Objective Evolutionary Algorithms can be implemented. These algorithms use logic similar to natural evolution theory, where a set of policies is considered a population whose characteristics (in this case, the parameters of the Radial Basis Functions) are related to the DNA of individuals. This process is repeated tens of thousands of times until each generation is almost identical to the previous one, indicating that the Pareto Front has been reached.

For more information, see:

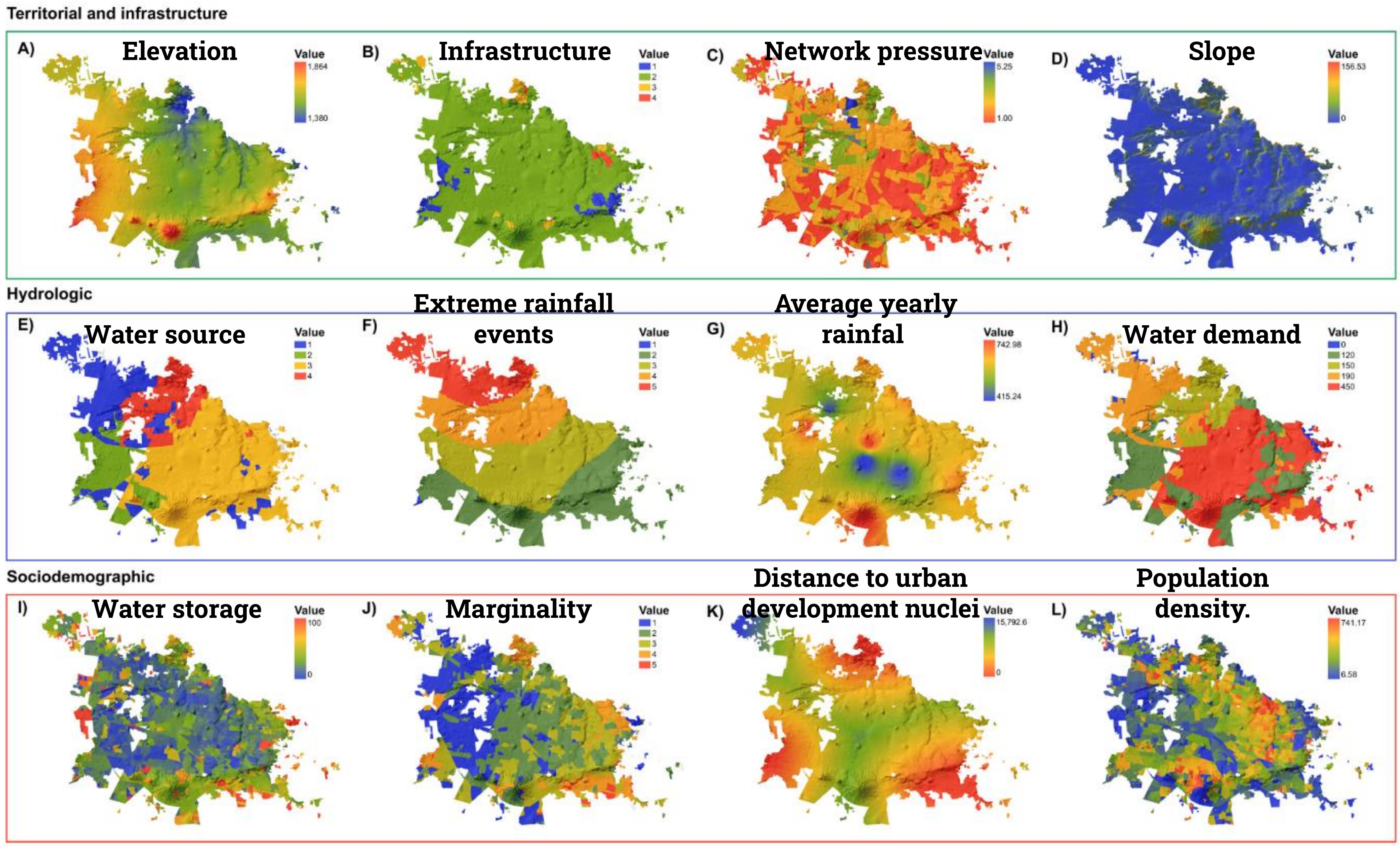
- On the operationalization of justice in multi-objective optimization: Xinying Chen, V., & Hooker, J. N. (2023). A guide to formulating fairness in an optimization model. Annals of Operations Research, 326(1), 581–619. https://doi.org/10.1007/s10479-023-05264-y
- On ethics of water and principles of distributive justice: Doorn, N. (2019). Water Ethics: An Introduction. https://rowman.com/ISBN/9781786609519/Water-Ethics-An-Introduction
- On Multi-Objective Optimization Algorithms with Radial Basis Functions: Salazar, J. Z., Kwakkel, J., & Witvliet, M. (2022). Exploring global approximators for multiobjective reservoir control. 55(33), 34–41. Scopus. https://doi.org/10.1016/j.ifacol.2022.11.006
- On Decision-Making Under Deep Uncertainty: Marchau, V., Walker, Warren E, Bloemen, Pieter J. T. M., & Popper S. W. (2019). Decision Making under Deep Uncertainty. https://library.oapen.org/handle/20.500.12657/22900

This document was developed as part of the workshop "How to Fairly Distribute Water When There Is Not Enough: Towards a Distribution Policy for the Aqueduct" as part of a joint research project between Tecnológico de Monterrey and TU Delft.

Appendix 7. Workshop Support Sheet – Characterization of SAs



Characterization Tool of Supply Areas – Made by the Author

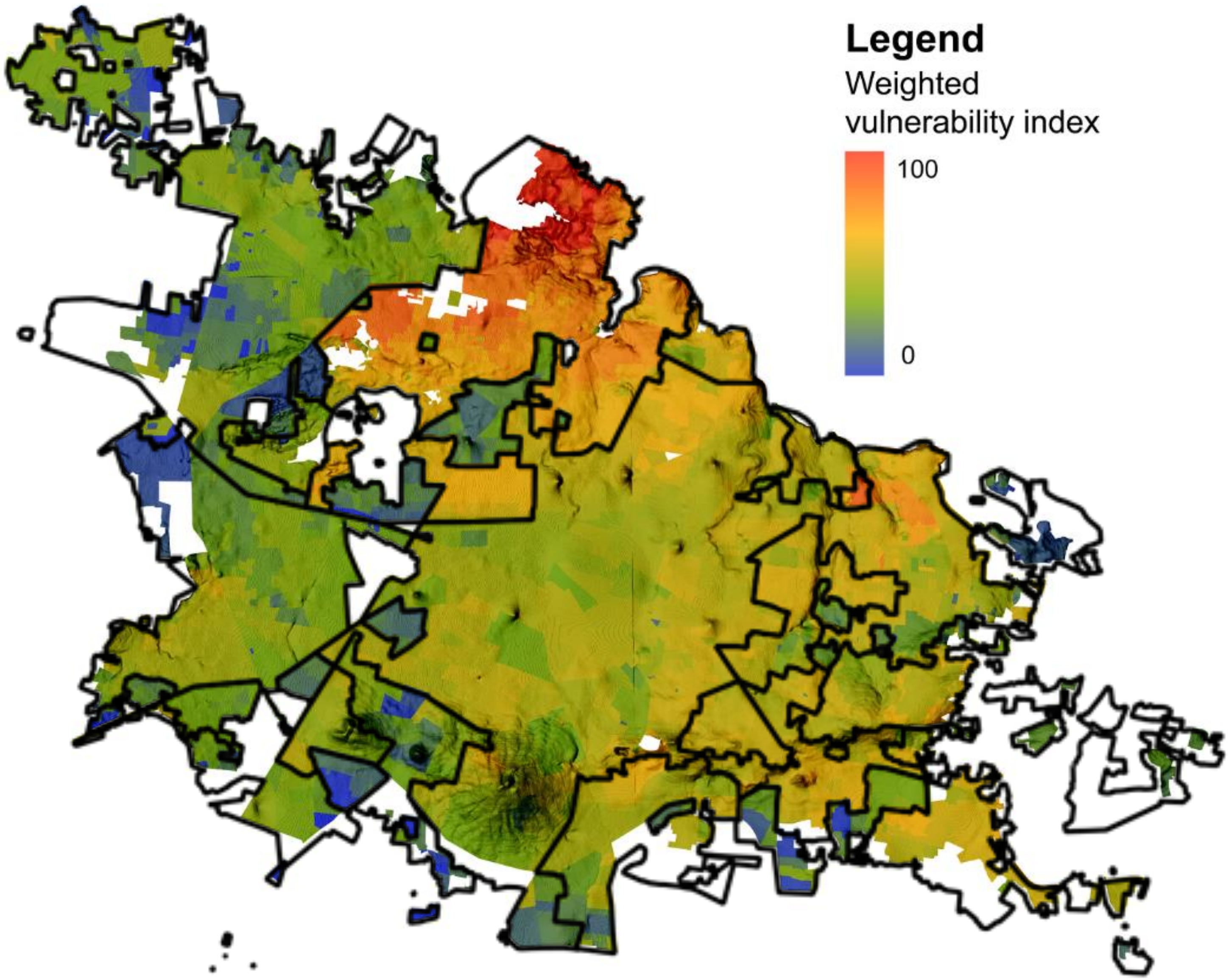


Spatial Distribution of Indicators Used in the Water Vulnerability Index. Extracted from Vazquez et al. (2022)

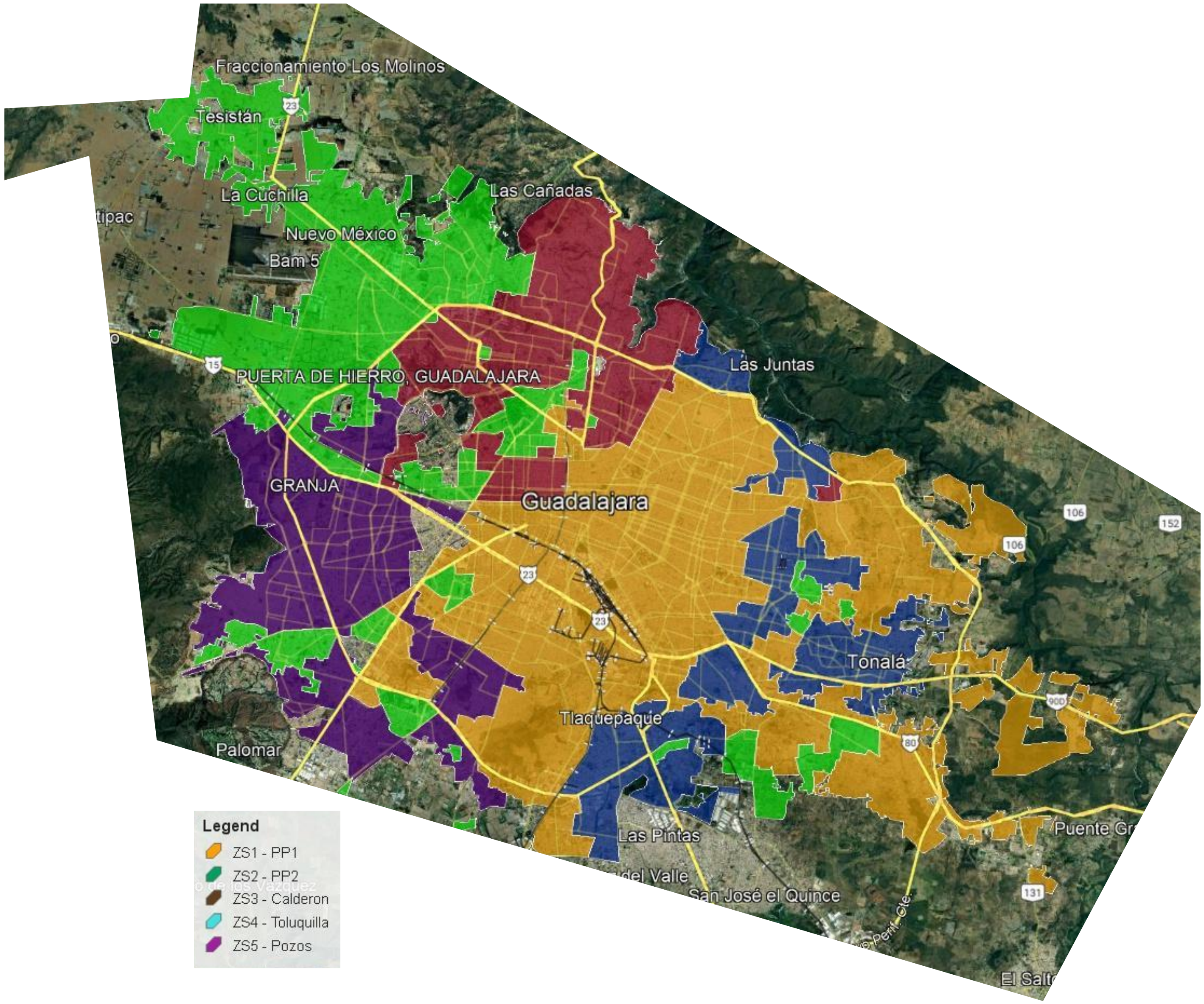
Description of indicators used in the vulnerability index extracted from Diaz Vazquez et al. (2022)

Category	Parameter	Description	Justification
Territorial and infrastructure	Elevation (m)	Digital elevation model for the study area.	Higher elevations demand higher energy flows to guarantee water access (Murphy et al., 1994). Communities and populations located in elevated areas are more susceptible to pressure fluctuations and thus, distribution interruption, due to mechanic failures or the lack of distribution infrastructure (Anand, 2011).
	Hydric infrastructure implementation (non-dimensional)	Areas with scheduled infrastructure investment for initial development or upgrading and/or recurring distribution interruptions based on the SIAPA and SGIA (Integral Water management Ministry by its acronym in Spanish) approved budget plans for the 2022–2023 period.	Areas with scheduled infrastructure investment were assigned the lowest priority (1), since the programmed works are aimed at improving water distribution and therefore their water scarcity risk will be reduced. BGUs with partial interruptions in their distribution network were assigned a higher priority (3) while areas identified with recurring water supply interruptions were assigned the highest priority (4). The remaining cover of the study area was assigned a value of 2, indicating no recurring disruptions in the distribution network were identified.
	Network pressure (Kg cm^{-2})	Average pressures within the water distribution network for all BGUs within the study area as reported by SIAPA.	Pressures within distribution networks are good indicators of the functioning of the network, as they are sensitive to pumping system deficiencies, increases in demands and infrastructure damages and leaks (Anand, 2011; Murphy et al., 1994). Areas with lower pressure have higher chances of distribution interruptions and are more sensitive to other distribution system failures.
	Slope (%)	Slope distribution model for the study area constructed based on the digital elevation model.	Urban areas tend to have low infiltration rates which quickly lead to runoff accumulation in impervious surfaces. High slope areas are especially susceptible to extreme rainfall events and are prone to slope failures due to extreme runoff accumulation, as well as drainage system overcapacity (Cristiano et al., 2017). Urban rain capture systems have the potential to reduce accumulated runoff, therefore, offering a mitigation strategy for runoff accumulation in urban areas (Sample and Liu, 2014).
	Water source	Spatial distribution of water source for the study area.	Water within the MAG distribution system is not obtained from a single source. Multiple sources, either superficial or groundwater reservoirs, are exploited to meet the urban area demand. These sources were classified by the State authorities based on the current water extraction volumes and the current population the sources supply with non-dimensional values ranging from 1 to 4. Higher values represent higher extraction volumes with respect to water availability. Following this recategorization the vector layer was rasterized for its integration.
Hydrologic	Extreme rain events	BGUs classification based on the probability of extreme rainfall events (Er),	The implementation of RWH strategies has the potential to reduce overall runoff volumes and reduce the risk of flooding during Er, which can be defined as rain events that surpass the 95% percentile distribution (Montijo-Galindo et al., 2020). The chance for Er was classified by State authorities with non-dimensional values ranging from 1 to 4 where higher values representing a higher chance for Er happening in each point of the study area.
	Rainfall	Spatial distribution of accumulated rainfall for the study area.	Although the average precipitations within regions of similar scale (724 km^2) are usually not statistically different, there are variations within the recorded precipitation within the area, mainly attributable to urbanization patterns and topographical characteristics of the area (Song et al., 2014). These spatial variations can have an influence on the rain capture potential of the areas within the study area and therefore the average annual rainfall was included in the study.
	Water demand	Water demand for the BGUs within the study area based on the mean water consumption rates for each of the analyzed neighborhoods reported by the State Water Commission based on the neighborhood grid	Water demand in urban areas tend to have large variability based on the population density, economic activity distribution, income, conservation measures, and distribution infrastructure, among others (Donkor et al., 2014). Higher demand areas are more susceptible to water scarcity due to increased water consumption rates and higher stress on the water distribution network (Donkor et al., 2014).

Category	Parameter	Description	Justification
Social	Percentage of households without water storage units (%)	Percentage of households aggregated by BGU without storage tanks or cisterns	Households without water tanks or cisterns are more vulnerable to water scarcity as they do not have access to water storage and are susceptible to water service intermittence and distribution failures (Fontanazza et al., 2013). The most recent (2020) national population and household survey (IIEG, 2022) was paired with the BGU grid to spatially represent the percentage of households lacking water storage units (water storage tanks or cisterns) for each of the BGU within the study area.
	Urban marginality	Urban marginality distribution for the study area, refers to the access of specific populations to household, income and educational goods and services (García Gil et al., 2012)	Marginalized populations have a higher risk to be affected by water scarcity due to a lack of public infrastructure and lower incomes (Ioris, 2016. As the aim of the present project was to allocate resources to mitigate water scarcity in the most vulnerable areas of the MAG, this parameter was included in the analysis to consider the socio-economical vulnerability of the population within the study area.
	Urban development nucleus distribution (euc.dist)	The state government has developed a program termed "Community Development Nuclei" (CDN). The aim of this program is to support specific marginalized urban polygons within the MAG by incentivizing economic, cultural, educational, and social development within these areas. This program was included in the present analysis by determining the Euclidean distance to the nearest Community Development Nucleus for the extent of the study area	Policies aimed at urban, social and spatial equality often require resource redistribution and prioritization to aid in reducing the breach between marginalized and non-marginalized communities within urban territories (Bailly et al., 1996), therefore, a higher priority was assigned to areas closer to a CDN as they are part of the previously described state program.
	Population density	Population density data for the BGU within the study area.	Income and economic activities are some of the main factors explaining water consumption variability among urban areas, therefore, water demand alone cannot clearly reflect the sociodemographic characteristics of the population affected by hydric stress (March and Saurí, 2010). Population density can be an indicator of the number of people and households affected by water shortages and failures in the water distribution system and therefore was included in the present analysis.



Weighted Vulnerability Index and Supply Areas. Modified from Vazquez et al. (2022)



Supply Areas contextualized. Made by the author.

Appendix 8. Feedback Survey Answers

Responses gathered via an online survey sent to the participants one week after the workshop. The table below was translated using DeepL free version.

Sector	Rate your overall experience in the workshop	What did you like most about the workshop?	What elements could have been improved?	Do you have any additional comments you would like to share with the organizing team?
Government	4/5	I found the first presentation extremely interesting, future scenarios are uncertain and planning in a big way in a scenario that is not fully confirmed would only focus efforts on a solution. When we can make a kind of acupuncture in small actions well focused attending each scenario as probable.	Time was somewhat limited and there was not much clarity on the objective of the workshop.	The support persons at the tables should act as moderators to prevent any one person from taking the floor, in addition to guiding the fulfilment of the workshop's objective.
Other	4/5	The analysis tool, its simplicity, and the ability of all participants to contribute.	Perhaps better explain the limits of the analysis and devote more time to the exercise.	Other cities do have transfer or aquaferic rings (Monterrey has had one since the 1980s and part of a second ring, and for the Valley of Mexico there are two lines, called "aquaferic" and "macrocircuit", although the circuit was never really closed). The equity approach is very interesting and innovative. It would be worth considering the tariff impact of water redistribution, just to clarify if the operator requires subsidy. Excellent work, congratulations.
Government	5/5	The methodologies presented and the exchange of experiences.	It seems to me that the experience could have been more grounded if the personnel who currently deal with the operation of the system had been invited to present the current situation.	Congratulations on the initiative and I hope it serves as a precedent for more events like this.

Appendix 9. Learnings from the Participatory Workshop Design and Implementation

The following key learnings were gathered from the organizers and participant feedback from the workshop.

What worked great

- **Scenario Exploration Tool as a Boundary Object**
  Building a common understanding of the problem through interactivity using an Attractive, intuitive tool to explore the problem and solution space and a simple task such as the one designed for Activity 1.
- **The Distributive Justice Objectives Cards**
  Laying down the Distributive Justice Principles in very simple statements proved highly successful in framing the discussion, keeping participants engaged and providing useful insights. The possibility of putting stickers to complete the objectives was also highly successful as it was easy to do. This approach to facilitating co-creation processes based on problem formulation for a MOO problem with Distributive Justice Principles is promising.
- **Short, engaging and non-technical presentations**
  Short and engaging presentations were possible by distributing supplementary material and thus avoiding overly technical presentations.
- **Building-up the need for a DMDU approach**
  In the first Activity, participants were allowed to tackle the decision-making problems with "conventional" decision-making tools. Multi-Objective Optimization was presented after the challenges of such conventional tools was clearly identified by the participants. Thus, not rushing to present a solution, and rather spending sufficient time in clearly communicating the complexities of the problem proved effective.

What could have worked better

- **Spend more time and resources on facilitator preparation**
  Due to time constraints, the facilitator training lasted around two hours. It would have been desirable to spend at least the same amount of time in training as the workshop duration to make sure that facilitators can clarify all potential questions and then more effectively support the workshop participants. A full workshop dry run is necessary for such a complex workshop.
- **Improve note-taking**
  A purpose made sheet for note taking was offered to the volunteers to guide them on what insights were note-worthy. However, this document was overly complex and slowed down their note-taking process. It would have been better to do a much simpler document in

Word and then distribute a document afterwards for putting the notes in a homogeneous format.

- **Mind table diversity**
  In a co-creating process, diversity is key. It is necessary to spend enough time on table planning and ensure timely confirmation of participants to avoid sectoral clustering.

What didn't work

- **Better navigate the trade-off between structured vs prescriptive workshop design**
  As we wanted to reduce the influence on the proposals following the non-prescriptive approach, some elements, such as clearly defining the scope of the policy were omitted, resulting in off-topic discussions and non-relevant insights for the research.