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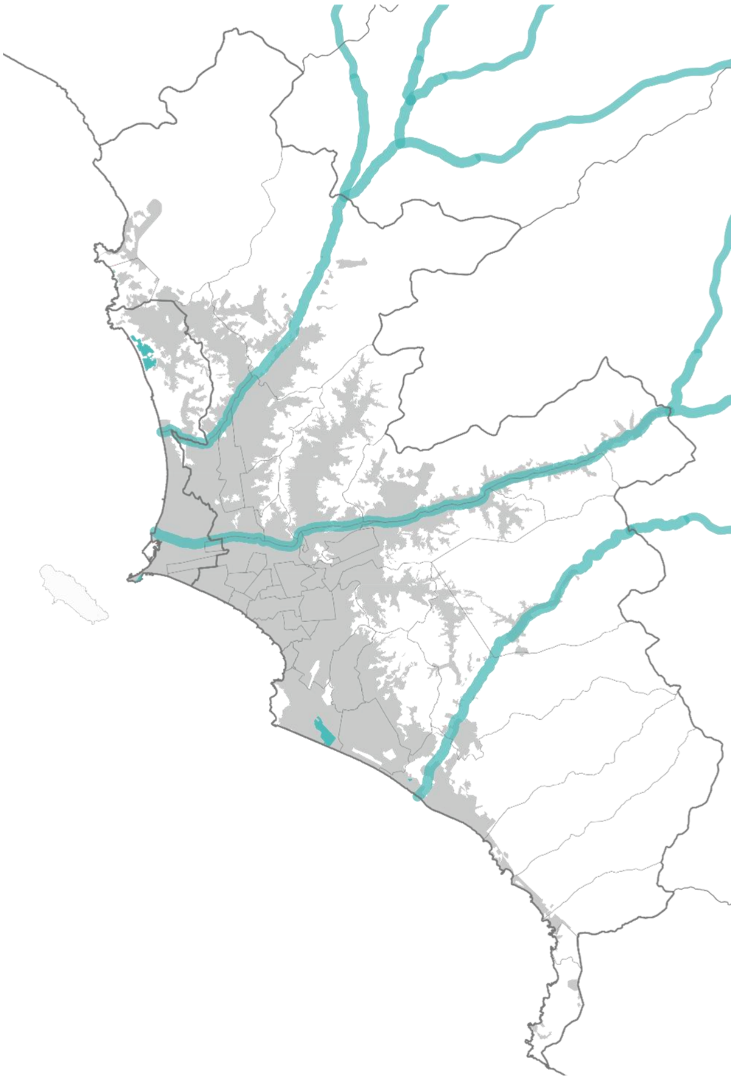

Master Thesis
M.Sc. Urban Agglomerations

Towards a Water Sensitive Urban Design (WSUD) Approach for Lima - Peru

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Abstract

Lima, the second-largest megacity located on a desert after Cairo, is currently facing a scenario of physical and economic water scarcity that, if not addressed, could lead to an irreversible situation for the metropolitan area. Various anthropogenic and natural factors have been demonstrated to produce more significant pressure on freshwater availability and decrease its quantity and quality, with greater emphasis on semi-arid environments given the existing natural conditions. This study aims to create a holistic water-sensitive framework for semi-arid environments by promoting an Ecological Infrastructure (EI) network. Furthermore, define a spatial proposal applied at different scales and outline governance recommendations to ensure Lima's transition towards a water-sensitive city (WSC). In this context, *ecological infrastructure* is defined as the network of green and blue infrastructure, natural and artificial, that make up the landscape of a semi-arid environment.

In order to test the hypothesis that Lima requires a holistic water-sensitive strategy to cope with the crisis, a multidimensional analysis of the inherent characteristics of the metropolitan area was carried out. Thus, the conditioning factors of the existing green and blue infrastructure, the governance system, and the urban metabolism that characterizes Lima's urban water cycle were examined. For the latter, the Urban Water Mass Balance (UWMB) method was applied, even though it has only been tested in developed and high rainfall environments. The results showed that the water crisis in Lima is aggravated by several interrelated factors, such as rapid population growth, the effects of climate change, weak governance, and unequal access to services, impacting the city's population, production, and ecological environment. The results also revealed that Lima's water demand depends almost entirely on a centralized system. In the face of low rainfall levels typical of semi-arid environments, wastewater and the recovery of wasted water from system leakage present a high potential to increase water in the city's system.

These results suggest that, unlike developed environments, to ensure the transition to water sensitivity, Lima requires transforming the city into a supply basin, providing ecosystem services, promoting water-sensitive communities, and providing equitable access throughout the territory. To this end, recognizing the water needs of the formal and informal areas that make up the city is essential. Thus, based on this knowledge, the research introduces a Vision as a unifying future state with a 15-year horizon that addresses all of the city's water availability challenges.

Keywords: Lima Water Scarcity, semi-arid environment, Urban Water Mass Balance (UWMB), Water Sensitive City (WSC), Water Sensitive Urban Design (WSUD)

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Moreover, I would like to dedicate this dissertation to my angel, my mom.

Abbreviations

AAA	Autoridad Administrativa del Agua
ALA	Administracion Local de Agua (Local Water Authority)
ANA	Autoridad Nacional del Agua (National Water Authority of Peru)
BGI	Blue - Green Infrastructure
CHIRILU	Chillón, Rímac, Lurín river basin
CR	Comité de Regantes (Irrigation Committee)
CRHC	Consejos de Recursos Hídricos de Cuenca (Water Resources Council of the River basin)
CRHCI CHIRILU	Consejo de Recursos Hídricos de Cuenca Interregional Chillón Rímac Lurín (Water Resources Council of the Interregional River basin CHIRILU)
DIGESA	Dirección General de Salud Ambiental (Peruvian General Directorate for Environmental Health)
DGIAR	Dirección General de Infraestructura Agraria y Riego (Department of Agrarian Infrastructure and Irrigation)
ECA	Estándares de Calidad del Agua (Water Quality Standards)
EDEGEL	Enel Generación Perú (Peruvian electricity company)
EI	Ecological Infrastructure
EPS	Empresa Prestadora de Servicios (Service Provider Company)
GDP	Gross Domestic Product
FAO	Food and Agriculture Organization of the United Nations
IUWM	Integrated Urban Water Management
IWRM	Integrated Water Resources Management
GORE	Gobierno Regional (Regional Government)
INDECI	Instituto Nacional de Defensa Civil (National Institute of Civil Defense)
INEI	Instituto Nacional de Estadística e Informática (National Agency for Statistics and Informatics)
IWCM	Integrated Water Cycle Modelling
IUWM	Integrated Urban Water Management
JASS	Junta Administradora de Servicios de Saneamiento (Community-managed service providers for drinking water and sanitation)
LCA	Life Cycle Assessment
LMP	Límites Máximos Permisibles (Maximum Permissible Limits)
MFA	Material Flow Analysis
MEF	Ministerio de Economía y Finanzas (Ministry of Economy and Finance)

MINAGRI	Ministerio de Desarrollo Agrario y Riego (Ministry of Agrarian Development and Irrigation)
MINAM	Ministerio del Ambiente (Ministry of Environment)
MINEM	Ministerio de Energía y Minas (Ministry of Energy and Mines)
MINSA	Ministerio de Salud (Ministry of Health)
ML	Metropolitan Lima
MML	Municipalidad Metropolitana de Lima (Metropolitan Municipality of Lima)
MVCS	Ministerio de Vivienda, Construcción y Saneamiento (Ministry for Housing, Construction and Sanitation)
NGO	Non-governmental Organization
OEFA	Organismo de Evaluación y Fiscalización Ambiental
OSINERGMIN	Organismo Supervisor de la Inversión en Energía y Minería (Energy and Mining Investment Supervising Agency)
PGRHC	Plan de Gestion de Recursos Hídricos de Cuenca (River Basin Water Resources Management Plan)
SDG’s	Sustainable Development Goals
SEDAPAL	Servicio de Agua Potable y Alcantarillado de Lima (Semi-Public company for drinking water and wastewater services in Lima and Callao, Peru)
SENAMHI	Servicio Nacional de Meteorologia e Hidrologia (National Meteorological and Hydrological Service)
SNGRH	Sistema Nacional de Gestión de los Recursos Hídricos (National Water Resources Management System)
SUNASS	Superintendencia Nacional de Servicios de Saneamiento (National Superintendency for Sanitation Services)
TAG	Tropical Andean Glaciers
UM	Urban Metabolism
UNDP	United Nations Development Programme (PNUD)
UWMB	Urban Water Mass Balance
UWC	Urban Water Cycle
WHO	The World Health Organization
WRL	Water Resources Law
WSC	Water Sensitive City
WSUD	Water Sensitive Urban Design
WTP	Water Treatment Plant
WWTP	Wastewater Treatment Plant

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Chapter 1: Introduction

1.1 Background: Water Scarcity and Water Security

Water is undoubtedly one, if not the most essential, natural resource for human development, and its value is possibly infinite (Vörösmarty *et al.*, 2010). Worldwide, 70% of the Earth's surface is water. This statement could lead one to think that it will always be abundant, but only 3% of the total water is freshwater (97% is saltwater). Most of it (99%) is in glaciers or is challenging to access because it is groundwater (Agudelo, 2005, p. 93). In other words, less than 1% of the available water on Earth should cover human consumption, subsistence uses, ecosystem protection, and production. Nowadays, the data reveals that one-third of the world's population is in a water crisis, suffering the physical effects of water scarcity at least once a year (Hofste, Reig, and Schleifer, 2019). According to Winpenny (1997), water scarcity occurs when the demand exceeds freshwater supply in a given area. Natural factors and human action can produce this. Another relevant number is that approximately 1.6 billion people face economic water scarcity; this means that although water may be physically available, they lack the necessary infrastructure to access it due, in many cases, to the inefficiency of institutions to guarantee it (UN, 2021).

In the face of water scarcity, several anthropogenic (artificial) and natural factors produce even more pressure on available freshwater and drive a decrease in its quantity and quality. Among the natural aspects is the heterogeneity in the spatial distribution of water reserves available for consumption. As shown in Figure 1, regions such as Latin America, for example, concentrate a more significant amount of available freshwater, approximately 30% of the total. In contrast, zones like Africa, the Middle East, or Oceania, also located in arid and semi-arid environments, have a significantly lower percentage.

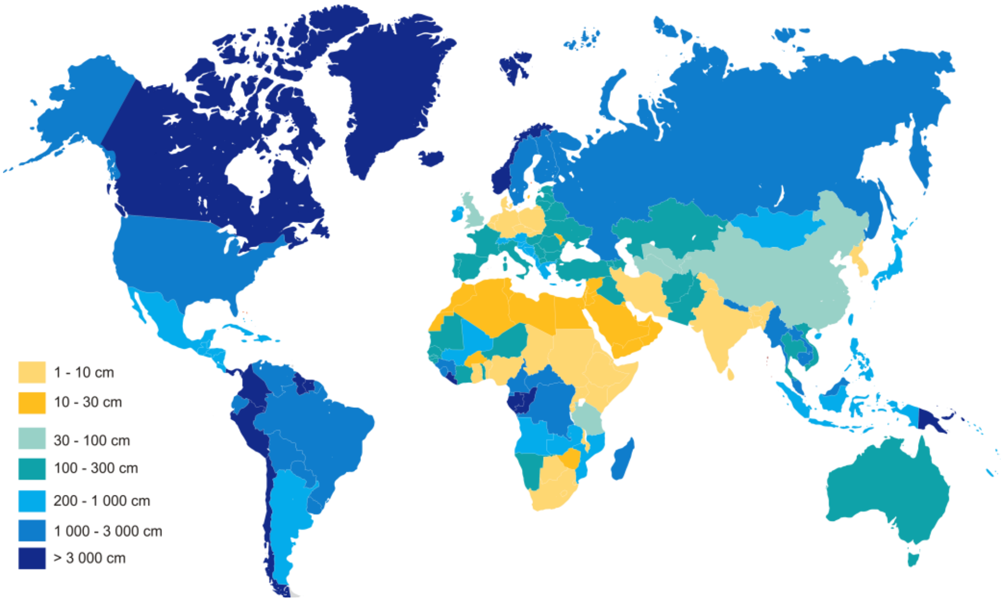


Figure 1: Spatial distribution of water reserves around the world.
Source: Created by author, adapted from Gassert *et al.*, 2013

The lack of natural freshwater supply leads many of these regions to depend intensively on groundwater, a resource that should be safeguarded in case of drought. This situation is because, in addition, there is a heterogeneous distribution also in the temporal aspect. Water is not stationary but instead circulates and constantly moves between the earth and the atmosphere. The process is called the hydrological cycle, and it is closely related to the climatic and geographical context in which it develops. Therefore, as shown in Figure 2, there is a predominance of water stress in countries located in arid regions of North Africa and the Middle East over the rest. Only in these regions are 12 of the 17 countries with extremely high water stress, and these scenarios are becoming more and more common (Hofste, Reig, and Schleifer, 2019).

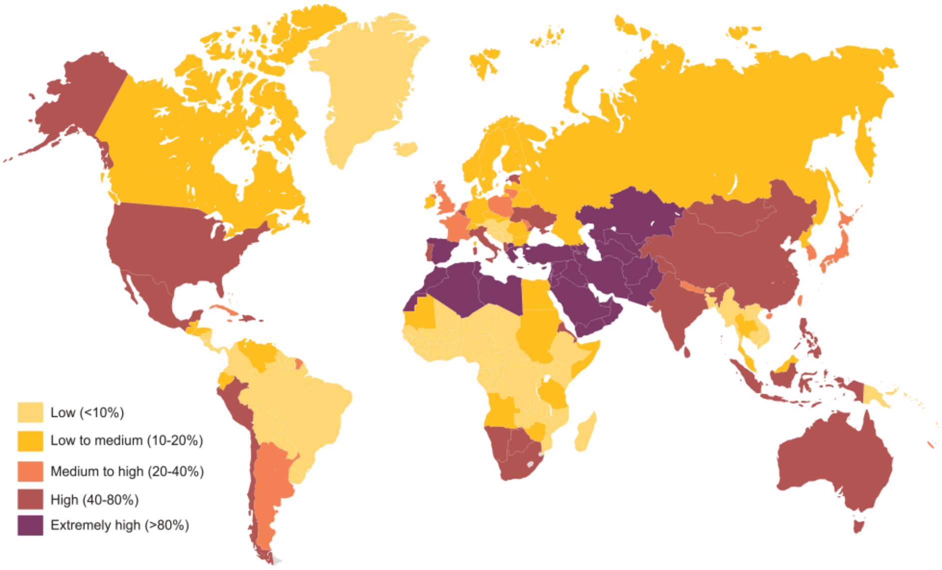


Figure 2: World Ranking of Water Stress
Source: Created by author, adapted from Gassert *et al*., 2013

According to a study conducted by the Research Water Institute, exponential population growth also has increasingly severe consequences on the availability of water resources (Otto, 2013). Over the last 100 years, the world's freshwater use factor has increased six-fold. Since the 1980s, there have been warnings of an increase in its use at a rate of 1% per year. Furthermore, it is expected to continue growing at a similar rate by mid-2050, when the population is estimated to reach 9.7 billion inhabitants (Guppy *et al*., 2017, p.3). In water terms, this implies a growth between 20% and 30% of current water use rates, further exacerbating the problem. The analysis is based entirely on the physical availability of the resource and the population's size (FAO, 2012). Several indicators have been established since the early 1980s, the best known and most widely used being the Falkenmark indicator, commonly called *water shortage*. The Falkenmark indicator calculates simply the annual water availability per capita. It uses the population within a given area and divides it by the volume of water (surface and groundwater) available annually. Water stress exists within the limiting ranges when the value is below 1,700 m^3 per capita per year. When the value falls below 1,000 m^3 per capita per year, it is called water scarcity, and when it drops below 500 m^3 per capita per year, it is absolute scarcity. In other words, the higher the population and the lower the water resources, the higher the degree of scarcity (Liu *et al*., 2017, pp 547).

Other determining factors that further aggravate the risk of water scarcity are climate change and water quality degradation in natural sources. During the last few decades, projections show a notable decrease in precipitation in semi-arid zones and a greater frequency of extreme phenomena such as floods and increased temperatures. This phenomenon results in a severe reduction in river runoff and minimal recharge in aquifers in arid and semi-arid zones of southern Africa, Australia, and the Americas, affecting the amount of water available for all uses (Bates *et al.*, 2008). On the other hand, poor water quality is another factor threatening its availability. Indeed, rapid urbanization, unregulated use of fertilizers and pesticides in agricultural areas, mining operations, high concentrations of population in informal areas, and poor waste disposal to natural sources often make water unfit for use with multiple consequences for health and the environment. These factors pose significant challenges for current and future water management, especially in countries with recurrent water scarcity due to their inherent characteristics (arid and semi-arid zones) or anthropogenic factors (UNESCO, 2015).

At the 2nd World Water Forum in 2000, the warning call was made: *"we simply cannot manage water in the future as we have done so far, or the economic network will collapse."* As a result of this warning, the concept of water security began to gain relevance, and today many countries have become aware of it. They have incorporated it into the agenda, considering it a priority for sustainable development. According to Grey and Sadof (2007), water security is essentially the availability of adequate water, in quantity and quality, for human supply, subsistence uses, ecosystem protection, and production (Paris, 2020, pp.13). In order to achieve this, institutional, financial, and infrastructure capacity is required for access and sustainable use of the resource. Another key element is to have a clear strategy to reduce the risks associated with its availability. An essential part to ensure water security is, without a doubt, to understand the importance of water not only as a resource in itself but also as a means or common thread to encompass the other dimensions of development, connecting every one of the Sustainable Development Goals (SDGs) (Wong, Rogers and Brown, 2020). Safe water implies food and energy security, disease prevention, improved quality of life, and ecosystem protection.

1.2 Problem Statement: Lima Water Crisis

Peru is considered one of the 20 wealthiest countries globally in terms of water, accounting for 1.8% of the total. However, this resource is distributed heterogeneously throughout the territory. Thus, the Peruvian coast concentrates more than 65% of the population but only has 2.1% of the total water produced nationally (ANA, 2019). Lima, the country's capital, located on the coastal belt, is the second-largest city after Cairo (9.5 million inhabitants), located on a desert and home to more than 10.5 million inhabitants (CPI, 2019, pp 8). Nevertheless, there is a difference in the hydrological framework between the two cities. Cairo, located on the border of the Nile River, has annual rainfall close to 25 millimeters (mm) per year, while in Lima, it is almost a fallacy to talk about rain since it only receives 9 mm in its annual peaks. In addition, the average flow of the Nile River is 2,830 m^3/s. In contrast, in the case of Lima, the average flow of the Rimac River, the main river that supplies the city, does not exceed 28.6 m^3/s annually and with very irregular patterns throughout the year due mainly to the melting of Tropical Andean Glaciers (TAG) (Said *et al*., 2014, pp. 667; SENAMHI, 2019).

According to a study conducted in 2016, the average annual per capita water availability is 125 m^3 per capita, four times lower than the absolute scarcity index according to the Falkenmark indicator, which means an alarming situation, as shown in Figure 3 (AQUAFONDO, 2016). Faced with the water scarcity scenario, if the climatic, geographic, and resource distribution conditions are not encouraging, the picture becomes increasingly complex when added to population growth. Lima is already home to 32% of the national population, and 14% live below the poverty line without regular water and sanitation services. The population has grown 14 times since 1940, and it is estimated that by 2035, more than

13 million people will inhabit the city (INEI, 2020b, p.7). In that sense, according to estimates for that year, water demand will increase by 40%, far exceeding supply (Stakeholders, 2020). Under the crisis scenario, the impact on the economic sector, services, and ecological systems would also be notorious. The city concentrates 46% of the country's Gross Domestic Product (GDP), and its electricity service is supplied entirely by hydroelectric plants located in the upper areas of the basin (Villar, 2019).

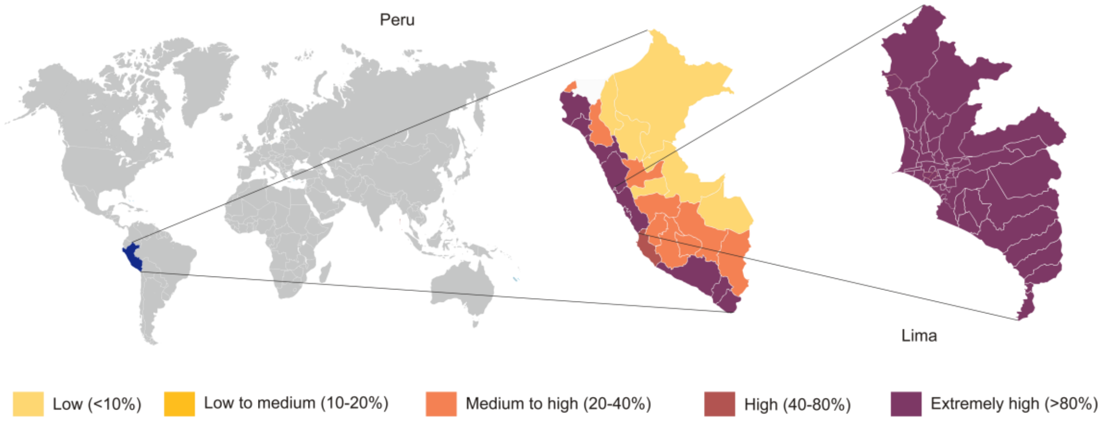


Figure 3: Water Stress in Lima
Source: Created by author, adapted from AQUAFONDO, 2016

The crisis also has repercussions on Lima's problem in providing and maintaining natural ecosystems and public green areas for the population, mitigating the impacts of climate change on them, and managing irrigation by using potable water in many municipal governments. According to estimates, the average amount of green areas is 3.06 m² / inhabitant, well below the nine square meters per capita recommended by The World Health Organization (WHO) in the context of RIO + 20 (MML, 2014). A reduction of anthropogenic (artificial) ecosystems and green areas would have social repercussions for the population, systemic effects for the city, and a drastic change in the city's landscape.

The problem analysis reveals that different factors aggravate the water crisis in Lima, which are organized through strongly interrelated and largely dependent layers: natural systems, demography vs. supply and demand, infrastructure, city morphology, climate change, and water governance. These factors will be analyzed in-depth in Chapter 4. Traditionally all the aspects are usually analyzed independently, or, in the best of cases, information is obtained from two interrelated layers. Therefore, the responses that have been outlined from different sectors, whether public or private, have been just palliative and do not achieve comprehensive solutions in the long term. There is a need for multidimensional analysis and the development of lasting and effective solutions. Tackling the complex problems of Lima's water crisis requires a change in the way water is managed. Consequently, an approach based on sustainability and the integration of all factors that aggravate it, one whose axis is to establish the long-term relationship with water, is needed.

One tool that can be applied is the Water Sensitive Urban Design (WSUD) approach to transition Lima to a Water Sensitive City (WSC). The WSUD approach integrates the water cycle with the natural and built environment through urban planning and design (Dolman and Zuijderwijk, 2011). This holistic approach combines hydrology, landscape architecture, and sociology. In that sense, a water-sensitive city is where the built and natural environment live in balance, diversifies its water sources, and transforms its population into water-sensitive communities (Wong, Rogers, and Brown, 2020). Both concepts (WSUD and WSC) will be explained in-depth in the second chapter (Theoretical Framework) of the research for further analysis and understanding.

1.3 Purpose, Research Questions, and Hypothesis

Based on the above overview of the problem of water scarcity and insecurity in the world, with particular emphasis on the multidimensional problem faced by Lima, the main objective of the research focuses on creating a holistic WSUD framework for semi-arid environments by promoting a cohesive urban Ecological Infrastructure network (Blue and Green). The second part of the research aims to define a spatial proposal that can be applied at different scales and could be replicated in several parts of Lima. In the last part, outline governance recommendations for developing the strategy to enable the transition of Lima into a water-sensitive city. In that sense, the question that guides the project and aims to be answered throughout the research is:

How could Lima successfully transition to a water sensitivity development?

In order to answer this question, the research is supported by eight secondary questions (SQ) seeking to analyze the theoretical framework, the context of Metropolitan Lima, and the design framework to develop a strategic vision. Each question has been assigned an objective to clarify the final product to be obtained by answering them. The questions are as follow:

1. SQ 1: What are the key factors to be considered in a WSUD Approach in semi-arid scenarios? / Identify the crucial aspects of the WSUD Approach.
2. SQ 2: What can be learned from existing Water Sensitive Best Practices to better elaborate a WSUD framework? / Analyze best practices for WSUD in semi-arid and multi-scale scenarios.
3. SQ 3: What are the characteristics of Blue and Green Infrastructure (BGI) in Metropolitan Lima? / Identify and localize the urban ecological infrastructure in Lima.
4. SQ 4: What is Lima's Governance capacity to address water challenges? /Identify the limitations and opportunities of Lima’s Water governance.
5. SQ 5: Which water flow has the most significant potential for improvement in the water system of Metropolitan Lima? / Identify through UWMB the flow with the most effective potential for substitution.
6. SQ 6: What are the main socio, ecological and spatial drivers of Metropolitan Lima's water scarcity and water insecurity? / Identify the drivers of water scarcity and water insecurity in Lima.
7. SQ 7: What strategies can support the transition to the WSUD framework in Metropolitan Lima? / Establish the holistic (spatial /governance) strategies for a better shift towards a Water Sensitive City.
8. SQ 8: How to adapt the strategy into a multi-scale design? / Establish water-sensitive vital projects focusing on an optimistic scenario.

Based on the objectives, as shown in Figure 4, the research aims to demonstrate how a holistic water-sensitive strategy that combines urban planning, integrated water management, and urban ecological infrastructure management can address the water crisis in Lima.

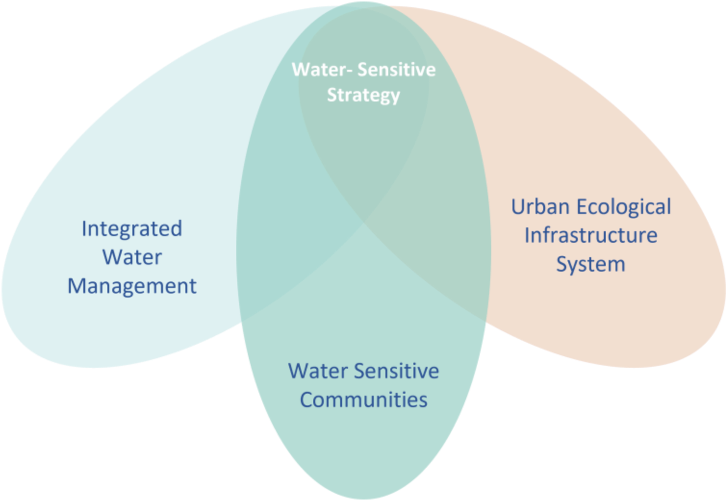


Figure 4: Hypothesis diagram
Source: Created by author, 2021.

1.4 Research Design

The research design is framed in five interrelated stages: the analysis of the problem and definition of the topic (1), the theoretical framework (2), the analytical framework (3), the design proposal (4), and finally, the outline of proposals in the framework of public policies, general recommendations, and conclusions (5).

The first stage (1) seeks to analyze water scarcity and water security in a global framework to understand the magnitude and complexity of the conflict. In this section, the first intention is to analyze the specific situation in Lima (Peru) from a local context. To this end, a series of interrelated layers are identified, ranging from environmental, governance, and even climate change, among others. These will be analyzed in-depth in section 3, so only general aspects are mentioned. A second intention of the section is to define the project. For this purpose, the objectives, hypothesis, and research questions are outlined. Furthermore, the methodology used for the development of the research is explained.

The second section (2) is based on a broad bibliographic review of literature on integrated water management, water metabolism, and urban ecological infrastructure and deepens on the theories, benefits, and tools of water-sensitive urban design and its close relationship with land use planning. This section intends to find a direct connection between water-sensitive strategies and the integrated management of green, blue and grey infrastructure. Also, to understand how these theories can manifest themselves spatially from the urban aspect and their relevance in the face of water scarcity. A second intention of the section is to introduce two essential elements to extrapolate them in the analytical approach of the following section. First, the spatial aspect intends to orient the vital theoretical elements for effective water-sensitive strategies in semi-arid environments like Lima. It answers the question: What are the key factors to be considered in a WSUD Approach in semi-arid scenarios? To this end, the section analyzes in-depth the Australian best practice. Second, from the aspect of governance and multi-scale development of a water-sensitive strategy, the section explores the best practice of The Netherlands. The conclusions seek to answer the question What can be learned from existing Water Sensitive Best Practices to elaborate a WSUD framework better?. This analysis will be done through primary and secondary sources from books, academic articles, reports from organizations, censuses, publications from government agencies, among other studies relevant to the topic.

The conclusions are drawn from the literature review and best practices in the previous stage, in the third section (3), seek to be extrapolated and merged to the Lima context. The focus of the section is based on an analysis of the inherent characteristics of the Lima metropolitan area in different aspects and determining the specific scales and locations that merit further intervention. The first intention of the analytical approach implemented in this section is to understand the main reasons that have led Lima to a situation of water vulnerability, analyze the role of the existing urban ecological network, and analyze the water governance in the city. Questions such as What are the characteristics of Blue and Green Infrastructure (BGI) in Metropolitan Lima? Moreover, what is Lima's Governance capacity to address water challenges? seek to be answered. A second intention is to obtain relevant indicators on water capacity by analyzing both natural and anthropogenic sources. The analysis focuses on water flows in and out of the city and determines resource efficiency through indicators. This section seeks to answer: Which water flow has the most significant potential for improvement in the water system of Metropolitan Lima? Finally, the unit's conclusions are summarized by answering the question: What are the main socio, ecological and spatial drivers of Metropolitan Lima's water scarcity and water insecurity?

The fourth section (4) is the so-called design section. It is based on the conclusions of the analytical framework of the third section (3) and the reflections outlined from the theoretical framework in the second section (2). The main intention of the section is to design a contextualized water-sensitive strategic framework for the city's metropolitan area based on the opportunities and limitations found. In that sense, it seeks to answer: What strategies can support the transition to the WSUD framework in Metropolitan Lima? A second intention of the design approach is to propose interventions from the spatial framework at different scales within Lima's metropolitan area, therefore answering the question: How to adapt the strategy into a multi-scale design?. The last section (5) intends to synthesize the main implications of the stakeholders, the recommended scaling, and the prioritization of measures for a correct management of the vision proposed in the fourth part (4). Finally, the section intends to develop conclusions in response to the main research question and present recommendations for future developments beyond the scope of the research.

1.5 Implications of Research

The research has two spheres of relevance, scientific and social. Regarding the first, water scarcity is currently one of the main problems facing cities worldwide and even more so when exacerbated by population growth and climate change. In the past and even today, water management has been reduced in many contexts to optimize single, isolated parts of the water cycle, thus consolidating supply security without considering other dimensions of the process. This approach compromises to a large extent multiple objectives not only in the water framework but also social, economic, and ecological costs, increasing the vulnerability of cities (Wong and Brown, 2009).

The research emphasizes the imperative need to establish a strong link between urban planning and water management in cities, especially in those settled under semi-arid conditions. In these contexts, it is necessary to close the knowledge gap on the sustainability of water resources. Given this need, the research seeks to contribute to bridging the gap by serving as a basis for urban environments facing similar situations. In addition, although the WSUD approach has already been adopted in developed contexts, in the Peruvian system and many other developing countries, the fragmented and traditional approach is still being used. Similarly, with the application of methodologies to analyze the urban metabolism of cities, there are few practical examples, and the research is an attempt to continue research on the subject. The study is also framed within the Sustainable Development Goals (SDGs) promoted by the United Nations. In that sense, the thesis contributes to the understanding and transmitting some of the SDGs and how academia can function as a catalyst to bring science into action. It is essential to highlight that the common factor among all the SDGs is water. Therefore, introspection in this field is a determining factor for the development of most of the 17 SDGs.

From a social perspective, access to water is a basic need and, as such, should be a priority, especially in semi-arid contexts. Water scarcity only exacerbates social and economic problems and deepens rifts in society by having a more significant impact on the most vulnerable population and those with less purchasing power. In the context of Lima, there is a notorious contrast between urban and peri-urban areas, where the inhabitants of informal settlements do not have access to water and sanitation services like the rest of the city (Mervin, 2015). Several determining factors aggravate the situation, but they are sustained mainly by water governance that does not respond equitably to the entire population. Improving the water governance system is a means to an end, primarily because it improves environmental quality and society's response without distinction to water scarcity and all the risks associated with the lack of accessibility to water (OECD, 2021a). In this sense, the research proposes a vision understanding that there is a need to generate an interrelation between the various actors seeking to create awareness for the efficient and responsible consumption of water and the primary requirement to cover the existing gap of essential services.

1.6 Methodology

The thesis development process is based on a mixed methodology to address the proposed research questions, combining quantitative and qualitative elements. Combining both approaches within the research seeks to understand the topic better and build more robust conclusions. To address both quantitative and qualitative aspects, primary and secondary sources from books, academic articles, reports from organizations, censuses, publications from government agencies, among others, will be used. It is also necessary to indicate that the information related to the city of Lima is mainly in Spanish, for which quotes, images, or maps will be translated to explain better the concepts related to the research.

1.6.1 Qualitative Elements

Some elements are not tangible, but they will contribute a lot to the research; this is the literature review case, best practices, Lima governance analysis, and policy review, which will be applied at multiple parts of the investigation.

1.6.2 Quantitative Elements

Part of the research focuses on the collection of numerical data and its subsequent analysis. First, in the framework of the study of the current situation of Green, Blue, and Gray Infrastructure in Metropolitan Lima, the numerical data allow the research to determine whether there is a deficit that fosters inequity in the population's access to water. The data collected are:

- The total land area and urbanized area
- The total land area devoted to ecological infrastructure
- Public Open Spaces
- Green Area

On the other hand, as another quantitative element of the research, determining the urban water mass balance in Metropolitan Lima will allow the investigation to evaluate the limitations and opportunities of the city's water system's behavior. Secondly, it will enable the research to justify the location of the pilot projects and support the proposed strategy.

Urban Water Mass Balance (UWMB)

An Urban Metabolism is an approach that quantitatively evaluates an urban area's metabolic characteristics (Meng and Kenway, 2018). The method proven to be a reasonable basis for assessing urban metabolism from the water aspect is the so-called Urban Water Mass Balance (UWMB). This tool allows quantitative measurements to analyze better water efficiency and hydrological performance of an urban system. This technique condensed in an equation created by Kenway in 2011 (Figure 5), incorporates all water flows, natural and anthropogenic (artificial) that enter, leave, and are stored within an urban environment with defined boundaries and under a controlled period (Kenway, Gregory and McMahon, 2011). Both concepts will be analyzed in-depth in Chapter 2 (Theoretical Framework).

Original Equation

Input (Qi) - Output (Qo) = ▲S

Input (Qi) = P+C+D and Output (Qo)= ET+Rs+W+G

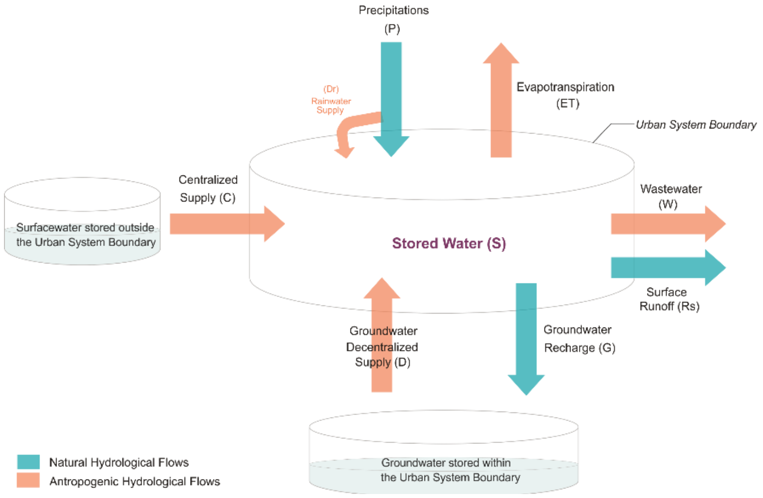


Figure 5: Original UWMB Equation

Source: Created by author, adapted from Kenway, Gregory, and McMahon, 2011

Where: P = Precipitation, C=Centralized Water Supply collected outside urban boundaries and may include imported surface water, groundwater or desalinated water, D= Represents decentralized water from groundwater (Dg) or rainwater tanks (Dr), ET= Actual evapotranspiration Rs= Is stormwater runoff, W= Is wastewater discharge (including sewage overflows), G= Is flows to groundwater, and ▲S= Stored water includes soil moisture, water in pipes, balancing reservoirs within the city, rainwater tanks, on-ground snow, and urban lakes (Kenway, Gregory and McMahon, 2011).

The following sections provide more details on the processes used to determine specific indicators.

Step 1: Select the Urban System: According to Kenway, an urban boundary must be defined and a controlled period for applying the tool. In the case of the research is Metropolitan Lima. The period 2016-2017 is the selected time window. This selection responds principally because it is the period of data with greater accuracy and reliability.

Step 2: Collect the Data: The second step is to collect data on water inflows and outflows. The investigation has used information gathered from multiple sources but mainly by the National Water Authority (ANA) in collaboration with the German Development Cooperation, the Observatorio de la Cuenca Chillon-Rimac-Lurin (CHIRILU), and the non-governmental organization AQUAFONDO, as shown in Table 1. It is necessary to make a brief precision on this aspect because although most of the data collected come from official sources, some assumptions were made. Therefore, to simplify the understanding of the quality of the data incorporated, a weighting was made according to pureness (exact data collected) or assumption (collection of data from various sources that after processing give a result). Thus, there are 3 degrees of quality: High (H), pure data that did not require any processing, Medium (M), data collected from more than one official source but required a mathematical analysis by the author, and Low (L), data collected from unofficial sources that required a mathematical calculation and whose result is based on assumptions made by the author.

	Water flows	**Sources**	**Quality**
Input	Precipitation (P)	INEI, ANA	M
	Centralized Water Supplies (C)	Observatorio de la Cuenca CHIRILU	H
	Decentralized Water Supplies (D)	Newspapers	L
	Centralized Recycled Water (Rw)	Observatorio de la Cuenca CHIRILU	H
Output	Wastewater (W)	Observatorio de la Cuenca CHIRILU	H
	Stormwater runoff (Rs)	Newspapers, Aquafondo	L
	Groundwater infiltration (G)	Observatorio de la Cuenca CHIRILU	H
	Evapotranspiration (ET)	Observatorio de la Cuenca CHIRILU	H
	System Loss (Cufw)	MML, Newspapers	L

Table 1: Data sources for calculating UWMB

Source: Created by author, adapted from Kenway, Gregory, and McMahon, 2011

Step 3: Adapt Kenway's UWMB Equation

Each urban environment has inherent characteristics due to its climatic conditions, geographic location, or even water management. In this sense, the UWMB framework described by Kenway was refined, the most relevant ones being the one carried out by Farooqui and colleagues in 2016 and later in 2018 by Paul and colleagues (Farooqui, Renouf and Kenway, 2016; Paul *et al.*, 2018). In the case of Farooqui (2016), de-centralized recycled water within and outside the selected urban system is incorporated into the original equation. Although this was a significant advance in refining the accuracy, it was still unclear how the approach could be adapted to developing country contexts. For example, it does not include components such as the loss of the system either by clandestine connections or losses in the piping system. This aspect is a highly usual and significant component (between 30% and 50%) when discussing water systems in developing countries (Paul *et al.*, 2018). Therefore, the equation modified in 2018 to establish the Bangalore UWMB does serve as a basis for Lima. Thus, the equation used in the investigation (Figure 6) incorporates decentralized recycled water and system losses.

Adapted Equation

Input (Qi) - Output (Qo) = ▲S

Input (Qi) = P+C +D+Rw and Output (Qo)= W+Rs+G+ET+Cufw

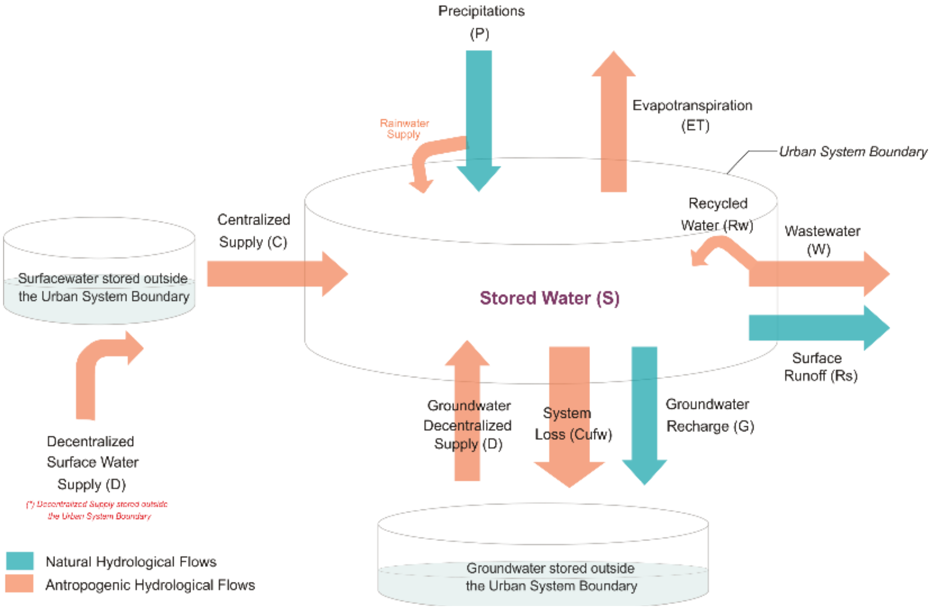


Figure 6: Adapted UWMB Equation

Source: Created by author, adapted from Kenway, Gregory, and McMahon, 2011; Paul *et al.*, 2018; Hegyi, 2019.

Where: P= Precipitation, C= Total Centralized Water Supplies (includes regulated and natural surface sources from rivers supplying Lima and groundwater extracted from the aquifer), D= Total Decentralized Water Supplies, Rw= Centralized Recycled Water, W= Total Wastewater, Rs= Total of Stormwater runoff, G= Total Groundwater infiltration, ET= Total Evapotranspiration, Cufw = System Loss, and ▲S= Stored Water (acting as control of mass conservation).

Step 4: Apply Performance Indicators: Based on the UWMB, the extent, and importance of natural and anthropogenic water flows within the selected urban environment. They also identify the degree of centralization of the system and further recognize which flows have the most significant potential to diversify water sources in a future water-sensitive strategy (Table 2). The supply centralization indicator gives the proportion of flows from sources external to the urban system. On the other hand, the rainfall harvesting performance indicator indicates the flow's proportion is captured and used locally. In contrast, the potentiality indicators show the ratio of (1) the centralized supply and (2) the total use that could be satisfied with the total volume (Kenway, Gregory, and McMahon, 2011). Another aspect of the performance indicators is that they allow comparison between two or more urban environments.

Water System Centralization	Supply Centralization	Centralized Supply/Total Water Use	C/(C+D) *100
Rainfall Potential for Water Supply	Centralized Supply Replaceability	Rainfall/Centralized Water	P/C*100
	Total Use Replaceability	Rainfall/Total Use	P/(C+D) *100
Wastewater Potential for Water Supply	Centralized Supply Replaceability	Wastewater Flow/Centralized Water	W/C*100
	Total Use Replaceability	Wastewater Flow/Total Water Use	W/(C+D) *100
Stormwater Potential for Water Supply	Centralized Supply Replaceability	Stormwater flow/Centralized Water	Rs/C*100
	Total Use Replaceability	Stormwater flow/ Total Water Use	Rs/(C+D) *100
Wastewater and Stormwater Combined	Potential of Total Water Use Replaceability	Wastewater+Stormwater)/Total Water Use	(W+Rs)/(C+D) *100
	Water Loss Recovery Potential of Total Water	Water Loss/Total Water Use	Cufw/(C+D) *100

Table 2: UWMB Performance Indicators
Source: Created by author, adapted from Kenway, Gregory, and McMahon, 2011; Paul *et al.*, 2018; Hegyi, 2019.

For the application of the UWMB method, some conversion factors have also been used based on the systems stipulated by the Food and Agriculture Organization of the United Nations (FAO) at the international level and the Peruvian level by the National Institute of Statistics and Informatics (INEI) (Allen *et al.*, 2006; INEI, 2016).

- 1mm (millimeter) is equivalent to 1 l/m^2 (liter per square meter)
- Hm^3 (cubic hectometer) is equivalent to 1 Mm^3 (million cubic meters)
- 1 Mm^3 (cubic millimeter) = 1 GL (Gigaliter)
- 1 GL (Gigaliter) = 10_9 l (liter)
- l/s (liter per second) = 0.001 m^3/s (cubic meter per second)

Additionally, the method applies runoff coefficients concerning the type of surface present in Lima and based on coefficients used in similar studies (Butler and Davies, 2004; Goh *et al.*, 2017)

Surface Runoff:

- Runoff coefficient urban area = 0.70.
- Runoff coefficient for paved area = 0.95
- Runoff coefficient for green areas = 0.15
- Runoff coefficient for agricultural area = 0.1
- Runoff coefficient for coastal area = 0.58
- Runoff coefficient for mountainous area = 0.3

1.7 Case Study and Scope

According to UN estimates, the world is an increasingly populated space; only in 2019 was the population 7.7 billion inhabitants and is expected to reach 9.7 billion by 2050. More than half live in urban areas. The largest have created urban agglomerations of more than 10 million inhabitants called megacities. Today there are 34 of them facing diverse environmental, social, economic, and infrastructure challenges (UN, 2019). This aspect sets megacities at the epicenter of sustainable development challenges. Nevertheless, as much as they are a space of risk, they also represent an area of opportunity, a kind of change laboratory.

Tackling water scarcity and ensuring water security for humanity is one of the biggest challenges facing sustainable development, even more so in urbanizations located in arid or semi-arid environments whereby nature there is a reduction in the availability of the resource. Lima, the capital of Peru, is the second-largest megacity globally, located in a desert area. It is currently facing a water crisis that requires immediate action, and it is expected that in the coming years, due to various factors, the scenario will be even more complex, impacting the country's water security. This sum of factors makes Lima a unique and relevant case study at the local level because of the impact the results could have on a larger scale. In that sense, the research results in Lima seek to function as generalities or patterns either holistically or individually for other urban environments in semi-arid contexts and under similar hydrological pressures. Nevertheless, to be effective, these generalities will require an adaptation to the inherent characteristics of the environment where they are intended to be applied.

The scope of the research covers the Metropolitan area of the city of Lima (ML), formed by the conurbation of the provinces of Lima and the Constitutional Province of Callao. For this research, throughout the following chapters, Metropolitan Lima will be recognized as ML. It is essential to mention that the investigation will not explore Lima's water management on a departmental or regional scale because it would require higher precision and time. However, it is worth mentioning that within the limits of ML, the Rimac, Chillon, and Lurin river basins (CHIRILU Basin), which are the most important for the city's water management, are analyzed. On the other hand, the analysis also considers the relationship between the city and the coastal area. Nevertheless, this will not be the subject of an in-depth or detailed analysis. Another aspect is that the thesis has a broad scope; therefore, it delineates a vision and draws comprehensive concepts rather than detailed design. Thus, the plans, views, and cross-sections presented throughout the three scales of intervention are only general proposals. Financial aspects and social acceptance of the population are not analyzed in-depth either.

The research also includes the use of best practices as references. Both are examples of successful cases of implementation of water-sensitive strategies in the world. The concept was even created in one of them. However, even though one might think that the choice was based on that undeniable fact, the reasons are somewhat different from this general analysis. The first best practice chosen is the city of Adelaide in Australia. The main reason for the choice is based on the adaptation of the strategy to a semi-arid environment. The best practice analysis adds to the subsequent adaptation and contextualization of a water-sensitive process in a desertic environment such as Lima.

The second-best practice is The Netherlands. The choice is based on a holistic understanding of the creation and implementation of water-sensitive strategies. From a governance perspective, it is imperative to analyze development at multiple scales of intervention and the roles of each stakeholder. The case study analysis adds up to a rational strategy design in the face of the different scales seeking to work in Lima.

1.8 Limitations and Assumptions

The main limitation of the research focuses on obtaining consolidated data on water management in Lima. First, from the government to private institutions, several sources handle data that do not coincide and are outdated, making the analysis difficult. Secondly, the research was carried out in Germany, not arranging a trip to Lima due to the current world pandemic. This aspect implied that the investigation was based only on information obtained from the web pages of the institutions and newspapers and, in some cases, scientific articles. However, for the research, even though it is not sure whether the quantitative data obtained are accurate and consolidated, it was sought to extract as much relevant data as possible and work based on it.

On the other hand, another of the main limitations for the project's development has been time, so the research had to adapt and prioritize results, especially in the design part. The representation of the mesoscale design and coastal interventions scheme is not the research's main result, so the level of development is not in-depth. Instead, the focus is on designing the spatial strategy at macro and micro scales and how they relate to each other. Although it was impossible to cover several relevant aspects, these will be incorporated as recommendations for future research in Chapter 7. Finally, another important aspect is the decision not to integrate interviews of key stakeholders due to time limitations.

1.9 Thesis structure

The research is structured in seven chapters. **The second chapter** reviews the theoretical guidelines and concepts necessary for developing the investigation through reviewing the existing literature. It explores ideas such as integrated urban water management, urban water metabolism, existing ecological infrastructure in an urban environment, and finally water sensitive planning and design as well as tools that can contribute to the development of a holistic strategy. Thus, the literature review provides the starting point for the research and better understands the existing scientific base to be contextualized and applied to ML.

Chapter 3 provides an in-depth analysis of the application of WSUD strategies by reviewing best practices from the Netherlands and Australia. The literature review of both best practices provides a greater understanding of integrated water resources management principles and the conditions it requires to be successfully applied in urban areas. The analysis also provides a better understanding of the role of urban planning in the approach. In addition, the chapter identifies the scales of interrelationships necessary for the development of water-sensitive strategies like the Netherlands. Finally, it identifies the ecological variables to be assessed in semi-arid environments such as Australia.

Chapter 4 contextualizes ML and briefly reviews the city's history and its essential relationship with water. The chapter examines water management in ML, its relationship with the different spheres (national, regional, metropolitan and local), and highlights the regulatory framework and public policies and the actors involved in current water management. In addition, the chapter analyzes the main inherent characteristics of the city, emphasizing the current situation of the urban ecological infrastructure. It quantitatively determines the attributes of

Lima's urban metabolism and the potential of its water sources in the face of Lima's transition to a water-sensitive city. The chapter summarizes the main drivers of water scarcity and insecurity in ML. It sets out the main challenges and opportunities facing implementing a water-sensitive strategy under a holistic approach. Finally, it presents a discussion synthesizing the insights and findings of the research.

Chapter 5 considers the applicability of a water-sensitive vision in ML as an alternative approach to current urban water management. The concept is developed by contextualizing the theoretical process outlined in Chapters 2 and 3 and adapting it to the inherent characteristics of ML analyzed in Chapter 4. The chapter sets a holistic vision by creating a cohesive system of the city's ecological infrastructure. The chapter frames principles, strategic objectives, and measures to guarantee water security for the population. It also explores the spatial relationship of the vision in the urban development of Lima using a design approach. To this end, three scales of intervention are identified, and the possibility of promoting a systematic transition of the vision is studied.

Chapter 6 presents the main implications for the proper management of the proposed vision. It also analyzes the links between the different chapters, establishes the main benefits and the phasing and prioritization of measures for a possible implementation of the strategy for ML.

Chapter 7 presents recommendations for further in-depth analysis outside the scope of the research or future studies. Finally, the chapter offers general conclusions to answer the general research question.

Chapter 2: Theoretical Framework

Water security in urban environments is under constant threat from various factors, both natural and anthropogenic. To address this problem requires going beyond conventional practices. The second chapter will provide a brief review and explanation of the theoretical concepts necessary for developing the research. Terms such as water sensitive city and water sensitive urban design are explored and the tools to create a holistic strategy. Therefore, concepts like integrated water management and the differences between centralized, decentralized, and hybrid systems, blue-green infrastructure existing in an urban environment, and urban metabolism as a framework for analyzing and modeling urban systems are also explored. In addition, the chapter will allow throughout the literature review to answer the first research sub-question: What are the key factors to be considered in a WSUD approach in semi-arid scenarios, providing the starting point of the research.

2.1 Water Sensitive City (WSC)

Sustainability is a concept that has been gaining relevance over the last decades. According to what was established by the Brundtland Commission in the "Our Common Future" Report of 1997, it is described as *"Sustainable development is a development that meets the needs of the present without compromising the ability of future generations to meet their own needs."* Moreover, it is based on economic, socio-political, and ecological pillars to develop sustainable communities (UN, 1987, p.1). Climate change and rapid urbanization processes require the urgent incorporation of sustainability into the global agenda. A transformation led by developed environments insofar as economic and social stability and technical ability make it more feasible to think of a future. On the contrary, in developing contexts, the capacity to face rapid changes and implement long-term solutions thinking about tomorrow is limited, making its adoption even more complex. Water plays a transcendental role in this vision for a better world, being a fundamental element for sustainable development. It is a necessary resource for human survival, socioeconomic development, and the balance of ecosystems. However, due to natural or anthropogenic factors, water management faces significant challenges to ensure its resilience to future uncertainties in water supply (UNESCO, 2015).

Faced with the need to create sustainable solutions with integrated approaches that address social, technical, economic, and environmental aspects, coupled with the consensus that traditional urban water management systems are insufficient to satisfy the needs of an urban environment, the *Water Sensitive Cities (WSC)* concept was born. This new vision of transforming cities into sustainable urban waters initially promoted from various sectors in Australia and today adapted to other environments in the world respecting the same guidelines (Singapore's ABC Waters, China's Sponge Cities, the United States' Low Impact Development, among others) are a response to this need to reorient existing infrastructures, institutions and capacities towards this new integrated approach (Wong and Brown, 2009; Wong, Rogers and Brown, 2020). To achieve this sustainable vision, as described by Brown and colleagues after a study of several Australian cities, a water transition is required, understood as a progressive historical evolution of water-social contracts. They are perceived as the values or agreements between various actors in society (government, private sector, communities) on water use. The study inferred six cumulative transition stages to pursue a shift towards a more sustainable future, a water-sensitive city (Brown, Keath, and Wong, 2009). The first three stages of transition are linked to what Newman called the *Transit City* of the 19th century; urban spaces unable to continue to manage their water locally in the face of growing needs. In response, they employed the *"big pipes in, big pipes out"* approach, a linear engineering system that bridged the water supply and sewage disposal gap (Newman, 2001, pp. 93-94). In essence, the three stages, as shown in Figure 7, represent the first modern steps in securing water supply, sanitation, and drainage, levels at which many cities in developing countries still find themselves. Today, viewed as a future state, the Water Sensitive City is *"the culmination of water supply, sanitation, flood protection and environmental protection strategies that ensure long-term sustainability, livability, resilience, and prosperity."* (Wong, Rogers, and Brown, 2020, p. 436)

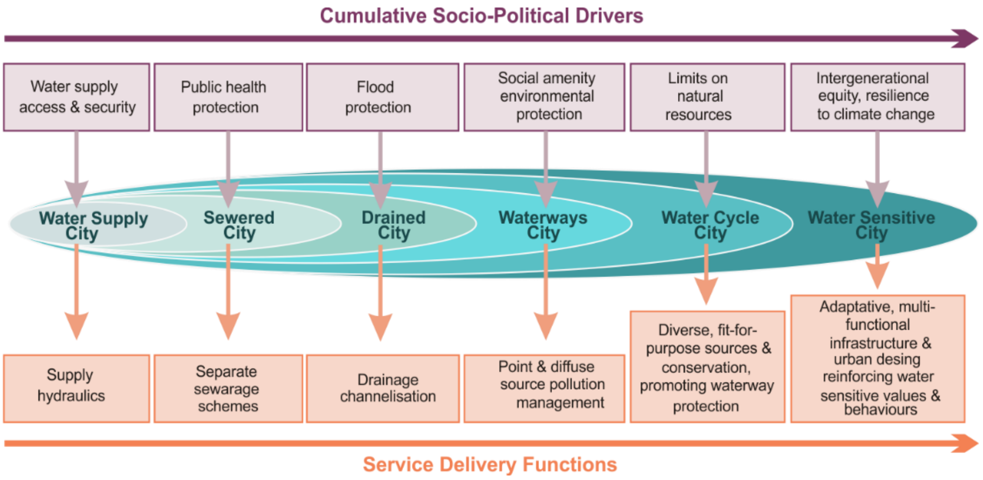


Figure 7: Water Sensitive Transition

Source: Created by author, adapted from Wong, Rogers, and Brown, 2020.

Wong also argues that implementing a WSC is based on three interdependent pillars that must be integrated into the urban environment: (i) Cities as Water Supply Catchments, (ii) Cities Providing Ecosystem Services, and (iii) Cities Comprising Water Sensitive Communities (Wong, Rogers and Brown, 2020, pp. 436-437). The first pillar implies that cities must have access to diversified water sources beyond surface water, runoff, or groundwater sources, understanding this as a combination of centralized and decentralized infrastructure that allows for water collection, treatment, storage, and delivery. On the other hand, and based on the second pillar, cities must provide ecosystem services by combining the built and natural environment, involving the integration of urban landscape design in urban water management to buffer the effects of climate change and increase natural capital for its various benefits. The third pillar implies that socio-political capital must be committed and sensitive to water within the framework of sustainability. This aspect entails having coherent behaviors (ecologically sustainable living), sustainable decision-making (seeking a balance between consumption and conservation), and developing professional development capacity for innovation. Although the principles provide guidance, the fact is that their application must be adapted to the context, understanding this as the set of biophysical conditions (geomorphology, hydrology, urban morphology, climate), local environment, and social and institutional requirements. All of them directly influence the adoption of water-sensitive practices (Wong and Brown, 2009; Wong, Rogers and Brown, 2020).

Currently, a limited number of urban environments, mostly in developed contexts and for reasons linked to climate change (such as drought or flooding), are transitioning to become water-sensitive cities. Examples in The Netherlands or Singapore are leading the process and are hotspots of urban innovation. There is not yet one that has reached the last stage of evolution, and its intersectoral integration would guarantee its productivity, competitiveness, and long-term sustainability. This situation is mainly due to obstacles that must be overcome, like institutional and technical factors. In most cases, it is not easy to increase the urban scale of the practice as planning still follows traditional patterns, and the development of an economic valuation of tangible and intangible benefits is needed to promote public-private sector investment. To address the challenges, Wong proposes working based on a holistic approach. The focus is on how the individual parts of a system interrelate to shape the whole system, the development of multidisciplinary knowledge and perspectives, the strengthening of long-term collaborative partnerships of diverse stakeholders, and the development of design processes integrating innovation, science, technology, and citizen participation (Wong, Rogers and Brown, 2020).

2.1.1 Transitioning to a sensitive city

Brown and colleagues define the transition as moving linearly from large-scale centralized infrastructures and institutions to integrated, distributed, and flexible infrastructure and institutions. In practice, while the complexity of evolution tends to create path dependency by reducing the range of options that are perceived to be viable, some possible transitional pathways can be developed. The transition following an S-curve pattern (going through a period of pre-development, acceleration, and stability) is ideal, as seen in Figure 8. A study conducted in Melbourne, the city in Australia with the most progress in transition over the last 50 years, provides important insights into what efforts should be focused on to ensure success. The dynamic framework is composed of six phases seeking to identify opportunities and constraints to transition. It starts with identifying the problem (Phase 1), identifying the causes (Phase 2), developing a shared understanding (Phase 3). A broad willingness of the parties to explore solutions characterized phases 4 and 5 are. The last phase is implementing a new water-sensitive practice (Brown, Rogers, and Werbeloff, 2016, pp.12-15).

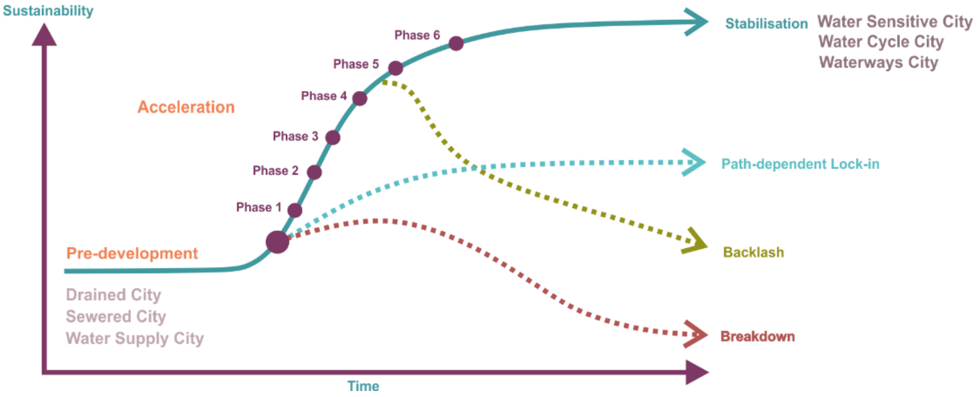


Figure 8: Transition Patterns towards a WSC

Source: Created by author, adapted from Brown, Rogers, and Werbeloff, 2016.

On the contrary, Armitage and colleagues suggest the need to adapt the linear evolution proposed by Brown by not contemplating the impact on the urban water cycle of factors inherent to developing environments. In that sense, aspects like formal and informal urbanization processes and undeveloped green areas constantly under pressure from urban growth shaped the transition. Thus, taking these aspects as a frame of reference, any evolution should consider two separated processes: urbanized areas equivalent to developed environments and informal settlements with limited infrastructure. The formal one is usually found as Drained Cities, requiring a transition that initially seeks to adopt integrated management of the urban water cycle, counteract polluting aspects to improve the quality of sources, and reduce water demand. On the contrary, informal areas are Water Supply Cities with multiple water and sanitation systems limitations. They require, in addition, to cover the urgent gap to grant secondary benefits to the population and contemplate maintenance aspects, being this a determining factor for success. Harmony should also be sought with the green environments, seeking their protection, and linking the populations from the beginning. As described by the author and as shown in Figure 9, this scheme would allow that at a given point in the process, both zones (formal and informal) transit under a system of equity towards a Waterways City (Armitage *et al.*, 2014).

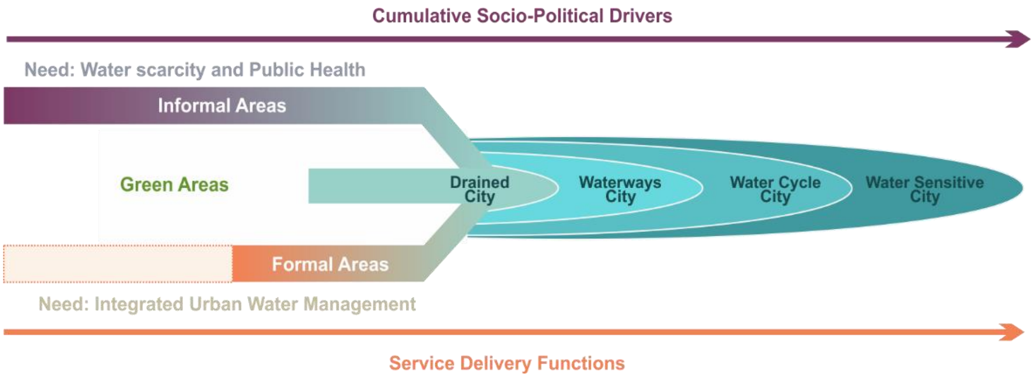


Figure 9: Adapted Transition towards a WSC

Source: Created by author, adapted from Armitage *et al*., 2014.

2.2 Water Sensitive Urban Design (WSUD)

Water Sensitive Urban Design (WSUD) is an approach formally developed by Whelans and Halpern Glick Maunsell in 1994, whose beginning is related to stormwater management in Australia. It is also known as Low Impact Development (LID) in the USA or Sustainable Urban Drainage Systems (SUDS) in the UK (Coutts *et al.*, 2013; Radcliffe, 2019). Nowadays, the approach is associated with Water Sensitive Cities (WSC) by facilitating the transition of the urban environment (in a scale-independent manner) towards water sensitivity through, as shown in Figure 10, interdisciplinary cooperation between water management, urban design, and landscape planning. The concept also takes the inherent conditions of the place as a basis (Dolman and Zuijderwijk, 2011, pp.18; Hoyer *et al*., 2011).

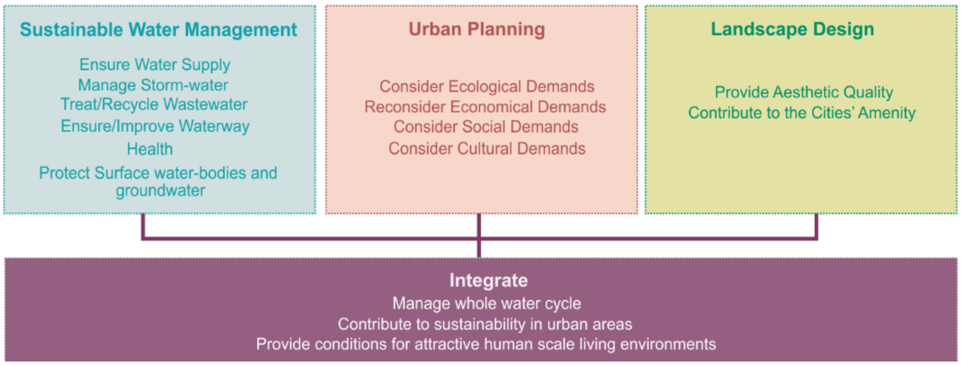


Figure 10: WSUD Framework

Source: Created by author, adapted from Hoyer *et al*., 2011

The overall approach that promotes the transition to WSC is context-specific, with no standardized solutions. However, merely referential ones, only the principles of practice are common. These principles referred to revolve around water sensitivity by bringing water management closer to the natural water cycle, providing aesthetic benefits, being functional by adapting to the surrounding environment and local conditions, providing multiple uses considering meeting the demands of all stakeholders with particular emphasis for recreational and nature conservation purposes, and their costs should be comparable to traditional solutions. Indeed, WSUD considers all parties and develops integrative strategies for ecological, economic, social, and cultural sustainability (Hoyer *et al*., 2011, pp. 29-34). However, its applicability presents obstacles since it is specific and requires technical capacity and diagnostic tools to develop appropriate solutions for each context. This aspect also implies the need for multidisciplinary teams, as solutions must be collaborative. Financial investments for experimentation and policies that promote integrated urban water management aligned with urban and territorial planning are also required (Wong, Rogers, and Brown, 2020).

Although WSUD is already extending towards integrated urban water cycle management, the fact is that in practice, it still tends to focus as in its beginnings on the management of rainwater and in contexts of abundant water resources and precipitation (Coutts *et al.*, 2013). However, due to its flexibility as it is site-specific, it can be implemented in semi-arid environments, although this is still at a theoretical level. Some studies determine that in dry contexts and where water appears in limited forms and with high seasonal variations, strategies must first understand the urban water cycle and adapt to it for more integrated results (Eisenberg *et al.*, 2013). In Australia, research suggests that WSUD elements have a high capacity to improve people's thermal comfort by reducing the high temperatures of the arid environment, especially when integrated with vegetation while promoting sustainable irrigation and soil moisture replenishment. However, the degree of benefit depends on multiple factors ranging from the existing climatic conditions, the design of water-sensitive elements to the nature of the landscape, or the choice of appropriate trees or vegetation (Coutts *et al.*, 2013).

2.2.1. WSUD Tools

As previously mentioned and reaffirmed by Woods-Ballard, each water-sensitive strategy is different in that each environment has inherent characteristics, advantages, and disadvantages that shape it. While the proper selection of methods for its application is essential, there is no one correct formula. However, the author emphasizes that the ideal solution usually employs several combined methods appropriate to the site's land use (Woods-Ballard *et al.*, 2007). For example, even though a pedestrian walkway is ideal for a stormwater canal, debris could negatively impact the solution if it is in the middle of a high-flow vehicular roadway. For applying the water-sensitive approach, a series of techniques or so-called tools have been developed and organized according to their primary function: stormwater use, treatment, detention and infiltration, conveyance, and evapotranspiration (Hoyer *et al.*, 2011).

Figure 11: Rainwater tanks
Source: Created by author, 2021.

Rainwater Use: The method has advantages from the practical aspect by collecting and using the resource on-site, reducing expenses associated with water management such as transportation, energy, and additional costs. It fulfills a double function by supporting water retention when necessary and being part of decentralized systems, making it even more attractive.

Among its main design elements is rainwater harvesting, which employs water storage devices underground or above ground, as shown in Figure 11.

Treatment: Before reusing water for domestic or productive purposes or increasing infiltration into the aquifer, an important step is treating the water. This method includes several design tools, including bio-retention areas, biotopes, and gravel or sand filters. The first (bio-retention areas), as shown in Figure 12, are depressions in the soil with vegetation in its interior whose mission is to filter pollutants and purify the water. They also have a double function; during dry seasons, they can be transformed into recreational areas. On the other hand, biotopes consist of a landscape where plants, whose mission is the natural oxygenation of the water, and animals are deliberately combined to achieve ecological stability (Figure 13). It is an aquatic element with significant landscape advantages by improving the quality of the environment. Gravel or sand filters function as filtration elements for areas with large volumes of runoff.

Figure 12: Bio-retention areas
Source: Created by author, 2021.

Figure 13: Biotopes
Source: Created by author, 2021.

Detention and infiltration: The detention method allows storage and infiltration to reduce surface water flows as well as the impact this generates on the sewer system. The main elements are roof retention or green roofs, green facades, permeable pavements, infiltration zones and ditches, wetlands, geo-cellular systems, ponds (dry and wet), and water squares, as shown in Figures 14, 15, and 16. In the case of green roofs and facades, they are based on multi-layered vegetation systems whose objective is to mitigate habitat loss in addition to their landscaping properties. Due to their porous condition, Permeable pavements allow water to pass through and then evaporate or be drained to a central system. Infiltration areas are planted spaces designed to retain and rapidly infiltrate surface water through a base composed of gravel, sand, or minerals. Swamps are linear elements that seek to store and conduct water. Therefore, their soil is impermeable. Cellular systems are prefabricated underground structures (not visible from the surface) to store and slowly infiltrate water. Other elements are retention ponds, which can be dry or wet. Dry ponds attenuate runoff flows and then infiltrate the water, while wet ponds store and retain the water and, when combined with biotopes, treat and clean the water. Water Squares are an innovation developed in the Netherlands; in essence, they are multifunctional spaces that retain water during rainy days and become public spaces for the population's enjoyment during dry times.

Figure 14: Rooftop system
Source: Created by author, 2021.

Figure 15: Porous pavements
Source: Created by author, 2021.

Figure 16: Watersquare
Source: Created by author, 2021.

Conveyance: This method allows water conduction, and within its main design elements are open channels. These, with optimal landscaping treatment, are an alternative to buried sewer systems whose perception as an essential element in the urban water system by the inhabitants is significantly weakened.

Figure 17: Pools and Fountains
Source: Created by author

Evapotranspiration: Although a natural process within the water cycle, today, the increase of paved areas in urban environments is drastically impacted, reducing its levels and increasing the effect of heat islands. This method allows regulating its levels by increasing green spaces and porous soils to promote passive evaporation. Other elements are rain walls, fountains, or pools that promote active evapotranspiration through water movement, as shown in Figure 17.

An important aspect is that although the tools present a process for their use, the truth is that each country offers additional information on regulations, construction, and dimensions for their application, so they must be adapted to each reality (Hoyer *et al*., 2011, pp. 17-22).

2.3 Integrated Urban Water Management (IUWM)

Understanding the *Urban Water Cycle (UWC)* is essential in the face of water-sensitive design as this knowledge provides clear definitions that can serve as a basis for further strategy development. While each component of the UWC is standardized, how they are interrelated is not, finding in each space a cycle adapted to the inherent conditions of the place. According to Marsalek and colleagues, the water cycle is the process that delimits the circulation of water through the biosphere, atmosphere, lithosphere, and hydrosphere. When it comes into contact with the urban environment, the cycle is drastically modified by the impacts of urbanization on the environment and the need for cities to provide water services to the population. The Urban Water Cycle results from this complex interaction (Marsalek *et al*., 2007, pp. 2-4). The UWC comprises two interdependent subcomponents, the stormwater discharge system, and the wastewater supply system. This reciprocal relationship between the two implies that changes in one of the components impact the entire system. In that sense, the addition (or reduction) of centralized, decentralized, or hybrid type water infrastructures causes changes in the overall urban water system (Sapkota *et al.*, 2015, pp. 156-157).

2.3.1 Centralized Systems

A centralized water system is one in which water for all uses is supplied, distributed, collected, treated, and drained through a single system (Cole *et al.*, 2018). For more than 100 years, urban environments have employed centralized systems to provide water and wastewater services. However, today it is under pressure in the face of increasing urbanization processes and other natural and anthropogenic factors that produce a misalignment of the system on the natural urban water cycle. Over the last few years, it has been demonstrated that alternative technical solutions are proving to be more efficient, especially in areas facing water scarcity, where centralized systems are highly vulnerable to prolonged droughts and the effects of climate change. Furthermore, according to a comparative analysis between Australian cities (which abandoned centralization) and Indian cities that manage water through traditional systems, modernizing or augmenting existing centralized water facilities is neither economically nor environmentally sustainable (Arora *et al.*, 2015; Sapkota *et al.*, 2015).

2.3.2 Decentralized Systems

Alternative systems widely used in developed environments are referred to as *Decentralized Systems*. Sapkota describes a system that provides water, wastewater, and stormwater services on a property (small scale) or cluster (medium scale) scale using alternative water resources. This system includes rainwater, wastewater, and stormwater, and its modeling depends mainly on the purpose it seeks to achieve. Among its benefits is the possibility of operating as autonomous systems or as satellite systems and more efficient use of resources. It also shows a reduction in transportation infrastructure costs (pipes, trucks) and long-distance water treatment, increased security of supply, strengthening the local economy, promoting more protected natural environments, and strengthening the sense of community and well-being of the population. Although its benefits show it to be a promising system in contrast to the centralized system, as shown in Figure 18, it also has limitations based on the lack of knowledge about long-term performance, operating costs, adequate governance, and initial levels of acceptance by the population (Sapkota *et al.*, 2015).

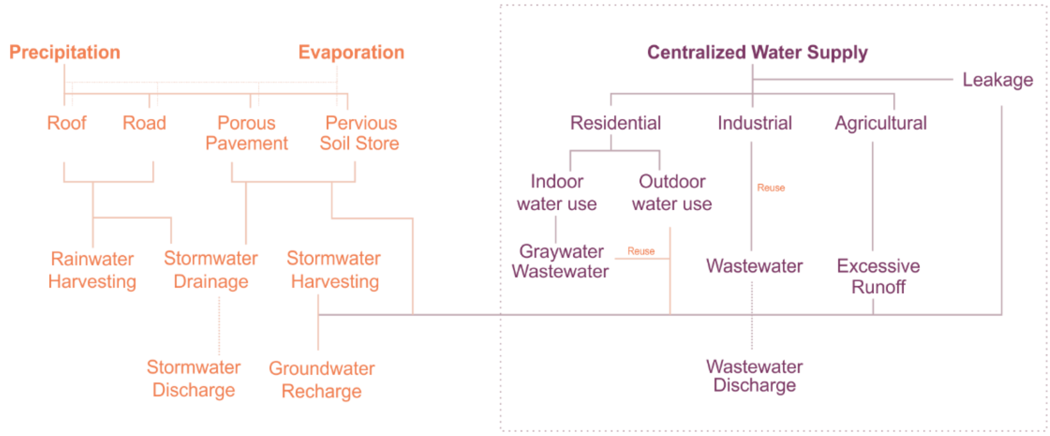


Figure 18: Decentralized vs. Centralized System

Source: Created by author, adapted from Sapkota *et al*., 2015.

2.3.3 Hybrid Systems

More sustainable water practices within urban environments involve moving away from the inefficiencies implicit in a concentrated system and towards diversification of sources, a concept also widely promoted by water-sensitive urban design approaches (WSUD). In 2009, Maheepala first employed *Integrated Urban Water Management (IUWM)* in a practical sphere. He defines diversification as *"a process that encourages water utilities to plan and manage water supply, wastewater, and stormwater systems in an articulated and coordinated manner to maximize their contribution to economic development and generate greater welfare"* (Arora *et al*., 2015, *p. 624).* Later, Lazslo and Krippner defined centralized and decentralized systems as complex interacting components, subsequently referred to as *hybrid systems*. Usually, decentralized systems are connected to centralized infrastructures and, by combining, they become part of a more extensive existing infrastructure system. Also, these hybrid systems are integrated with catchment systems, either anthropogenic (infrastructure) or natural forming part of the urban water cycle (Arora *et al.*, 2015). In essence, a hybrid water management system is a system that provides water services through the combination of a centralized water supply system with decentralized water supply options. In addition, this hybrid system offers greater water security by having more significant potential for large-scale sustainable resource consumption (Daigger and Crawford, 2007). Other advantages are the reduction of resource consumption due to the decrease in infrastructure and technology to treat all water with the same level of quality, promotion of solutions based on nature, high flexibility, and multifunctionality from the particular aspect allowing the saving of open space and decreasing its mono functionality, and the possibility of integrating other services such as recreational and cultural activities.

Although Integrated Urban Water Management is highly promising from a vision in the field, the truth is that IUWM has an interdisciplinary nuance that escapes the practical sphere. According to the United Nations, although water is a vital resource and plays a determining role in societies' social and economic development, it is imperative that its treatment not be seen in isolation. Under this new understanding of IUWM, the concept becomes much broader and globally accepted deriving to *Integrated Water Resources Management (IWRM)*, according to what is stated by Global Water Partnership (GWP), is *"a process that promotes the coordinated management and development of water, land and other related resources, in order to maximize economic outcomes and social welfare in an equitable manner without compromising the sustainability of vital ecosystems"* (Hassing *et al*., 2009, p.3).

While the integration of hybrid systems in an Integrated Water Resources Management strategy offers a wide range of benefits, the transition poses many challenges from a socio-economic and technical perspective that need to be addressed. The design and implementation of a hybrid system imply a deep knowledge of the water demand required and often knowledge impacting the project's spatial and temporal aspects. This aspect is associated with increased greenhouse gas emissions (GHG) due to higher energy consumption. From the social sphere, the adoption of diversified water sources still faces significant resistance from the public, influenced mainly by the social and cultural perceptions that revolve around the use of recycled water. On the other hand, from the legislative side, several regulatory gaps affect reliability and increase costs. Addressing these challenges requires adopting an integrated systems approach to the design and management of these systems that includes all dimensions of the systems (Arora *et al.*, 2015).

2.4 Blue and Green Infrastructure (BGI)

A combination of natural and artificial elements shapes the landscape of urban environments and affects their inhabitants' form and behavior throughout history (Ahmed, Meenar, and Alam, 2019).

2.4.1 From Green Infrastructure to Blue and Green

Green infrastructure (GI), understanding infrastructure as a physical management system that offers multiple functions and services, was born during the 1990s in the USA. According to Benedict and MacMahon, the concept implies an interconnected network of natural or anthropogenic (artificial) systems that benefit the population and conserve the value of natural ecosystems. The objective of GI is to be the ecological framework for ensuring the sustainability (social, economic, and environmental) of an urban or rural setting (Benedict and MacMahon, 2002). From the spatial dimension, GI, because of its relevance, should be seen as an integral concept necessary in planning at the urban and regional scale, allowing the strengthening of existing ecosystems in the environment through the generation of an interconnected system through corridors (Eisenberg *et al.*, 2013). Later, Ahern complements the concept of GI by interpreting it as a system and network of natural landscapes protected by built, artificial, and hybrid landscapes being beneficial not only for the population but also in the promotion of sustainable coexistence. The author alludes to the need to create resilient public spaces not to disturb the ecological ecosystems (Ahern, 2007).

The standard term *Blue and Green Infrastructure (BGI)*, closely related to GI, although used less frequently and with a more engineering nuance, refers to the combination of green infrastructure (including blue bodies) and ecological networks, a concept that the European Commission reaffirms. The EU understands BGI as a network of natural and semi-natural areas incorporating green or blue spaces (aquatic ecosystems), coastal and marine terrestrial zones offering a range of ecosystem services. Indeed, the concept of BGI originated in Brazil in response to the need in Sao Paulo to plan for the creation of integrated green and blue systems to address the risks associated with flooding that periodically impact the city (Ahmed, Meenar, and Alam, 2019). This transition from GI, which emphasizes green and natural, to BGI suggests broadening the approach to an integrative concept that, under the spatial dimension with urban water management, recognizes other ecosystem services by including green, blue elements, and artificial elements interventions. Ghofrani describes it as *"an interconnected network of natural and designed landscape components, including water bodies and green and open spaces, which provide multiple functions such as (i) flood control, (ii) water storage for irrigation and industry use, (iii) wetland areas for wildlife habitat or water purification, among many others"* (Ghofrani, Sposito and Faggian, 2016, p.499).

The new conceptualization of BGI, as shown in Figure 19, moves away from previous engineering discourses and allows a stronger linkage with water-sensitive design (or complementarity). This aspect is possible by interpreting blue infrastructure as the totality of blue elements (rain, rivers, among others) and green infrastructure as a network of landscape systems combining natural and artificial elements (open spaces) and whose purpose is to provide ecosystem services related to the urban water cycle. According to Ahmed and colleagues, this notion of artificial elements also allows for greater recognition of a series of ecosystem services such as water treatment, air cooling, as well as social or cultural benefits that are already developed in intentional man-made elements (Ahmed, Meenar, and Alam, 2019). This group could include everything from what Foster and colleagues call conventional gray infrastructure (storage structures, pipelines, canals, streets, among others) to public spaces like squares and communal areas and even physical infrastructure that provides a service such as high voltage towers (Foster, Lowe, and Winkelman, 2011, p.2; Eisenberg *et al*., 2013).

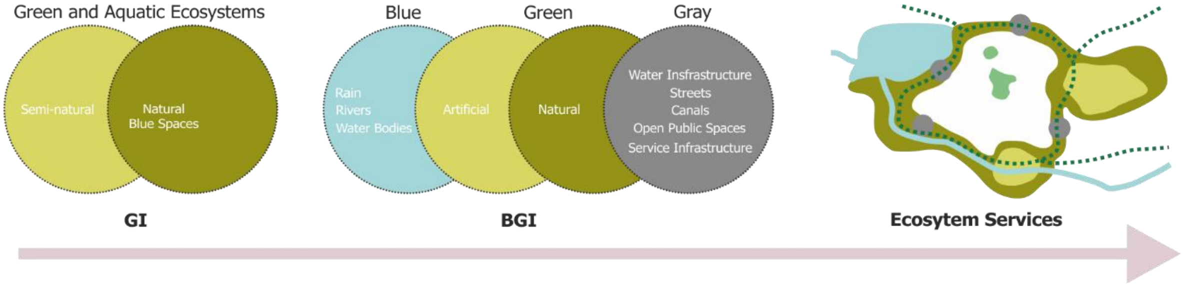


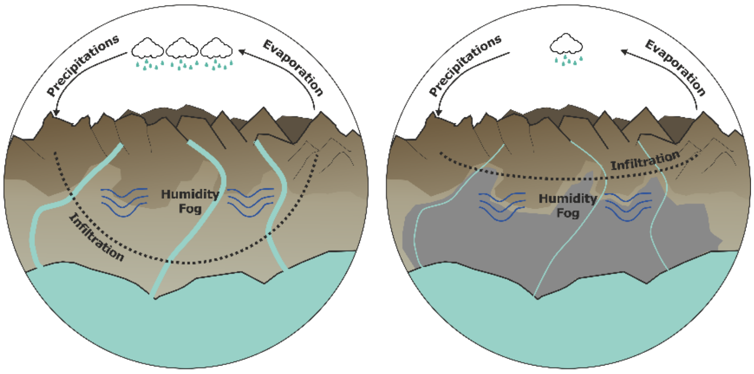
Figure 19: From GI, BGI to Ecosystem Services

Source: Created by author, adapted from Eisenberg *et al*., 2013.

Nevertheless, within the framework of urban planning, it should be mentioned that historically in many parts of the world, green infrastructure has been seen as an element with multiple ecosystemic benefits but "untouchable" when it comes to meeting social demands. This dissociation only encourages the expansion of metropolitan areas and more significant pressure on ecological regions. As Bogunovich states, it is necessary to move from conventional planning based on centralized grey infrastructure and with no relation between city and region to a decentralized symbiosis of diffuse limits between green, blue and gray elements (Bogunovich, 2012, p.8). This integration has been well accepted in China through examples such as Sponge Cities. The approach incorporates the natural landscape to provide more adaptive urban planning and resilient measures against climate change. Other examples of incorporating this symbiosis are The Netherlands and Sweden (Ahmed, Meenar, and Alam, 2019; Sun *et al*., 2020).

2.4.2 Blue and Green in semi-arid environments

Another strategy decanted from the application of BGI in urban and spatial planning is the understanding of where it is needed and the knowledge of how to design or manage its adaptability, especially in semi-arid or arid environments, as shown in Figure 20. For urban environments with desertic climatic and geomorphological conditions, green is a misleading term described by the LiWa team in a study conducted in Lima, Peru. Consequently, they propose an evolution of the concept towards what they call *Ecological Infrastructure (EI)*: *"the term ecological is closely linked to biodiversity, to the concepts of nature conservation and ecosystem services,"* and not to *"greening, beautification activities and the intention to create green-looking environments."* EI is multidisciplinary and incorporates, like BGI, a more significant number of artificial elements and infrastructure, whether green or gray (Eisenberg *et al*., 2013, p.62).



Natural semiarid environment Semiarid urbanized environment

Figure 20: Semi-arid Urban Water Cycle (UWC)

Source: Created by author, adapted from Eisenberg *et al.*, 2013

2.5 Urban Metabolism

Cities are by nature complex and evolving systems with patterns of flows and networks of connection with surrounding environments that transcend their territorial boundaries. The city's vision is no longer a set of static and individual parts isolated and disconnected (Maranghi *et al.*, 2020). As stated by van Timmeren and Henriquez (2013), *Urban Metabolism (UM)* is a new approach that implies the understanding of the inherent metabolic process of the city, being this a complex system as stated by Marangui (Timmeren and Henriquez, 2013). Indeed, UM poses parallelism between cities and ecosystems with the behavior of organisms. The similarity centers on the need for urban environments to consume resources from their environment and develop waste by transforming raw materials (such as water) in their process. Thus, urban metabolism flows in and out of the environment as a self-organized ecosystem (Kennedy, Pincetl, and Bunje, 2011). Although the term metabolism has its origins in the book *"Capital: Critique of Political Economy"* by Karl Marx written in 1894 and used to characterize the complex nature-society relations, it is not until 1965 that Wolman proposes the concept seeking to summarize the ideas around the analysis of the environmental effects of human activities (Beloin-Saint-Pierre *et al.*, 2017). Since then, a significant number of new associations and theories to urban metabolism have emerged, among which three ecologies stand out: industrial, Marxist, and urban, each included in aspects of multiple disciplines, but with a common thread.

2.5.1 Industrial Ecology

The metaphorical conception of metabolism in Marxist ecology is associated with the nature-society relationship, a central aspect in its two trends (metabolic rift and urban political ecology). The concept has a qualitative nuance as it is primarily used to highlight inequalities in power relations in urban environments. In industrial ecology, metabolism uses nature as a model and is associated with the analogy between urban environments and biological organisms regarding waste and energy processing. The approach focuses on determining flows into and out of an urban environment through modeling tools and quantitative methods. Its purpose is to understand the impact of urban processes on the system and establish efficient strategies to optimize and conserve matter; however, limitations need to be complemented. Industrial ecology does not provide information on the functioning within the urban environment, only on the flows that enter and leave it, which the approach calls a black box. In the case of urban ecology, unlike industrial ecology, it focuses on urban ecosystems and the functional links with and between the subsystems that make it up. However, addressing complex internal ecological flows presents a limited sense of the urban (Newell and Cousins, 2015).

As described, each ecology presents diverse ways of applying metabolism in urban settings with advantages and limitations. From a water perspective, adopting UM as a framework for analyzing and modeling complex urban systems assumes an understanding of their dynamics through the quantification of flows, recognizing in industrial ecology a more coherent approach for that purpose. Likewise, under this approach based on adopting the model of nature, UM seeks a path to the natural conditions of the environment to establish an efficient system, an intention it shares with concepts such as water-sensitive cities (Renouf *et al.*, 2016).

2.5.2 Urban Water Mass Balance (UWMB)

There are several approaches to water assessment related to urban metabolism through industrial ecology, like Life Cycle Assessment (LCA), Integrated Water Cycle Modelling (IWCM), Material Flow Analysis (MFA), and Urban Water Mass Balance (UWMB). Nevertheless, they stand out with considerable differences. The first, Life Cycle Assessment (LCA), primarily used in developed countries, is characterized by assessing the environmental impacts of urban water systems, focusing mainly on wastewater. The LCA approach served as the origin for developing a more recent one called Environmental Footprint, which determines the water footprint by quantifying the total water used in the life cycles of the products and services consumed by the inhabitants. The fact is that interest has been aroused in coupling UM with the LCA and Water Footprint assessment approach to represent a global metabolism of cities. However, its usefulness for assessing urban systems from a broader viewpoint, encompassing all flows and not only wastewater, is still under development.

On the other hand, the IWCM approach, although it integrates water flows as a whole, does so at the local scale and not at the city scale, limiting a complete picture of UM. Urban metabolism studies usually employ the Material Flow Analysis (MFA) approach, which quantifies the flows of resources (water, energy, carbon, materials, pollutants, and others) through an urban system. The MFA approach provides a snapshot of centralized potable water use at the city level from a water perspective. However, its effectiveness is limited by considering inflows and outflows as a whole, not accounting for individual resources in a specific way, and ignoring water flows from natural sources (Renouf *et al*., 2016, pp. 15-17). If what is sought is to have a complete understanding of urban water metabolism in a specific environment to cope with water scarcity and ensure water security for its population, the limitations of the MFA highlight that a more comprehensive assessment framework is needed. Indeed, the Urban Water Mass Balance (UWMB), unlike the MFA, does allow for a more thorough analysis of resource use and efficiency by focusing on water alone, as shown in Figure 21. This aspect enables considering all urban water cycle components (rainwater, imported supply, decentralized water, wastewater, stormwater, evapotranspiration, groundwater recharge, and water reuse), rather than counting only inflows and outflows (Paul *et al.,* 2018, p. 2).

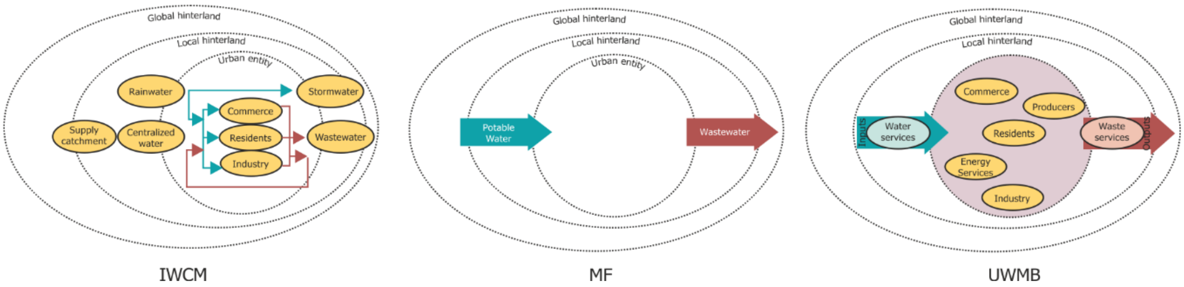


Figure 21: Integrated Water Cycle Modelling (IWCM), Material Flow Analysis (MFA), and Urban Water Mass Balance (UWMB)

Source: Created by author, adapted from Renouf *et al.,* 2016.

According to Kenway and Meng (2017), *UWMB* analysis is an approach that allows a complete account, including all water inflows, outflows, and storage. It is more frequently adopted to assess urban water systems (Meng and Kenway, 2018). However, it has certain limitations. From the technical side, the approach offers a set of performance indicators allowing a better understanding of the characteristics of the urban cycle, the linkages between flows, and the potentialities of each. Nevertheless, they still rely on estimations and interpretation of results without a more robust and standardized framework. On the practical side, the approach has been widely used in Australia, showing that large flows of rainfall, stormwater, and wastewater pass through urban areas without being harnessed. However, this framework has not yet been tested with real cases in developing countries. It has done so only at a research level and with the folly of adopting modifications as explained in the Methodology section of Chapter 1 (Paul *et al.*, 2018).

What is certain is that UWMB given its ability to generate performance indicators and even when developing its results involves employing assumptions, offers a reasonable basis for evaluating urban metabolism. The method is even more efficient and holistic than the traditional Supply-Demand balance by measuring the performance of an urban system rather than just the water infrastructure present in the urban environment. In that sense, mass balance shows itself as a promising approach that aligns with the objectives commanding a transition towards a WSC.

Currently, the need to diversify supply promoted by the water-sensitive approach to address water security implies an evolution in the way to view and value water in urban areas and assess its flows. In that line, the method finds in the UWMB a valuable tool to maximize the functionality that water offers (Renouf *et al.,* 2016, pp. 18-19). However, and as previously mentioned, the UWMB method (and other similar ones), given its limitations and shortcomings, needs to be complemented with auxiliary methods for a better understanding and exploitation.

Summary of the Chapter

Throughout the chapter, the literature review allows the study to answer the first research sub-question, What are the key factors to be considered in a WSUD approach in semi-arid scenarios?:

Adapt WSC principles: In the context of climate change and rapid urbanization processes, one of the growing challenges facing cities worldwide to cope with water scarcity is to ensure resilience in the water supply. In order to meet water needs, cities require a shift from traditional and ineffective systems to comprehensive and sustainable approaches. Over the last few years, various concepts and methods of urban water cycle assessment have been developed to provide alternative tools to achieve the objectives soon. The literature review explores the main aspects of the Water Sensitive City (WSC) concept recognizing it as a future scenario. It also shows that the transition from a traditional coverage model (water, sanitation, drainage) is being led by developed context as its stability allows thinking about a future. In that sense, they take the first steps to access diversified water sources, establish a harmonious relationship between the built environment and ecosystems and capitalize on engaged communities. Although these are the principles on which the transition is based, they only function as guidelines in practice. They can be adapted to the context in which they are inserted as long as their adoption directly influences the results.

Adapt linear transition to cover physical and environmental needs by implementing a WSUD vision: The transition from centralized infrastructures and institutions of a Drainage City to integrated, distributed, and flexible ones tend to create a dependency on the path to follow, reducing the range of options perceived as possible. Cases such as the Melbourne transition show that commitment, follow-through, and investment are required to sustain change. Otherwise, undesirable alternatives such as system breakdown could emerge. In the case of developing contexts, on the contrary, it is necessary to adapt the linear transition to cover the initial inherent needs of informal and formal areas in the city, being these very different and needed to have equity as a base. In order to meet the challenges, it is proposed to work based on a holistic approach such as that offered by Water Sensitive Urban Design (WSUD) through interdisciplinary cooperation between water management, urban design, and landscape planning. The literature also highlights that while there are no standardized solutions in applying water-sensitive approaches, it requires an alignment to principles. They are framed in a close relationship between the urban water cycle of the environment and provide multiple benefits (aesthetic, functional, and social) while integrating with the ecological systems of the site. In the case of semi-arid environments, while the degree of benefit depends on multiple environmental factors (climate, nature of the landscape, and others), some examples demonstrate the need to align the various water-sensitive tools to improve thermal comfort given the high temperatures and the promotion of sustainable irrigation systems to preserve green areas. However, more research is required in practice as the approach still tends to focus on stormwater management.

Integrate with the ecological infrastructure (EI): The evidence also reveals that facing the need for a water-sensitive approach to integration with the surrounding environmental systems, concepts such as Blue and Green Infrastructure (BGI) gain relevance. The main reason is that it incorporates natural and artificial blue and green elements (open spaces) by recognizing that they provide ecosystem services related to the urban water cycle. The knowledge, analysis, and application of articulated BGI systems allow a better and more sustainable link between the approach and the urban environment. Cases such as China prove successful and even provide greater resilience of cities to climate change. However, in the case of semi-arid environments, and evolution of the concept to Green Infrastructure linked more to biodiversity is proposed as the understanding must start from where it is needed and how it is required to be designed.

Implement hybrid systems: The water-sensitive approach also promotes introducing an Integrated Urban Water Management (IUWM) model to move away from the inefficiencies in a concentrated system to the diversification of sources. The use of decentralized systems shows promise, but not when taken as a stand-alone system. For greater effectiveness, given the limitations that it still presents in practice, it needs to be annexed to larger centralized systems. These diversified hybrid systems are much more efficient in areas of water scarcity and with semi-arid characteristics as they are not as vulnerable to climate change as their predecessor and are even more economical and environmentally sustainable. However, their application faces technical and legal gaps that need to be filled and the rejection in some cases of the population that deserves special attention.

To understand the urban water cycle specific to the site: The literature review also shows that given the complexity of cities, with particular emphasis on semi-arid environments, ensuring transitionality requires a better understanding of the urban water cycle and the metabolic processes of the urban environment. In that sense, the concept of Urban Metabolism in the field of Industrial Ecology presents empirical advances to develop comprehensive analyses adopting the model of nature. To this end, Urban Metabolism is aligned to a series of assessment methods (LCA, MFA, IWCM, UWMB), with the UWMB being the one that presents the most promising results by contemplating the natural and artificial water flows that enter, are maintained, and leave an urban environment. Furthermore, given its alignment with the sensitive approach, and if complemented by the analysis of other determinants of the urban water cycle of a city (geography, topography, climate, social aspects, and others), the UWMB could become an integral methodological tool to achieve the objectives of a Water Sensitive City. However, given the lack of applied cases, it is still too early to make this statement, and more examples in developed and especially developing countries are needed to advance.

Chapter 3: Best Practices

This chapter will take an in-depth look at the implementation of WSUD strategies by reviewing two best practices: the Netherlands and Adelaide in Australia. The literature review of both will provide a better understanding of water management principles and the conditions required for successful implementation in urban areas. The analysis will also provide a better understanding of the role of urban planning in this approach by identifying the scales of interrelationship necessary for the development of water-sensitive processes, as in The Netherlands. In addition, through introspection of the Adelaide strategy, the methods applied in semi-arid environments will be evaluated and the considerations necessary for its success. In addition, the chapter will allow through the literature review to answer the second research sub-question: What can be learned from existing Water Sensitive Best Practices to better elaborate a WSUD framework?

3.1 Netherlands: A Multi-level Approach

The Netherlands is recognized worldwide for having one of the most innovative and efficient stormwater defense systems in recent decades. Nevertheless, its understanding of water goes beyond just protection. Today, employing a holistic and multilevel approach, its study and analysis is an essential element in the research of water governance systems to apply water-sensitive urban design strategies. The Netherlands faces the North Sea and shares borders with countries such as Germany and Belgium. The territory is divided into multiple parts and is crossed from southeast to northwest by three rivers and a vast network of canals. More than 20% of the country is currently below sea level (representing 21% of its population), and another 60% of the territory is only one meter above. A hybrid system characterized the water governance system in the Netherlands, being the result of a long and complex evolution from a hierarchical and centralized approach that failed in the face of significant floods that put the country in checkmate (Rijkswaterstaat and the Association of Dutch Water Authorities, 2019, pp. 13- 46).

In January 1953, a severe storm hit the Netherlands; the post-World War II defense systems were severely damaged and could not contain the impact. More than 20 thousand hectares of the territory were flooded, forcing more than 70 thousand citizens to flee out of the country and leaving a toll of more than 2 thousand people (Mahiques, 2018). The crisis triggered the progressive change in its water governance system. After this breaking point, the Dutch Delta Work Program was developed, mainly based on flood protection. This first step in the country's water history has earned it wide recognition. More than 700 km of storm barriers and dikes distributed across 14 14 individual infrastructures, among which Oosterschelde (a 3 km long barrier) and Maeslant (last built-in 1997 near Rotterdam and consisting of two long movable parts) protect the country's coastline (Rijkswaterstaat and the Association of Dutch Water Authorities, 2019, p.45). However, during the last decades, they started to suffer the impacts of climate change, leading them to take their second historical step in water management, prevent. Severe flooding due to increased rainfall, collapsed drainage systems, intense periods of drought in hot seasons, and river overflows due to increased flow are some of the impacts they have faced. It was time to propose long-term solutions with a holistic vision.

3.1.1 Multilevel water governance

Multilevel governance refers to the various levels that distribute tasks and functions throughout the different phases that comprise it while sharing the same objective. It is not only a representation of the decentralization of functions but of the need to establish relationships at both horizontal and vertical levels (Morejón-Santistevan, 2019). Water management in The Netherlands is a nationwide effort that involves different administrative scales and spatial dimensions. Moreover, it starts from the premise that it is a responsibility of the country's public authorities, the government being the leading actor, but also of the different participants that make it up, including civil society organizations, the business community, among many others. The governance framework in The Netherland is decentralized and hybrid not only from a functional but also from a territorial perspective (Pahl-Wostl, 2019). However, and as previously mentioned, this was a long process of adaptation over the past decades seeking to bridge political (roles, functions, and regulatory framework), funding, technical capacity, and even participatory gaps.

The Water Law (2009) designated the public authorities responsible for water management. Afterward, the Administrative Agreement on Water Issues in 2011 emphasizes that water management is a shared responsibility. The problem of one is the problem of all. The Agreement specifies the duties and the instruments of each actor, which are interrelated to the Delta Plan the following year (2012) (OECD, 2014). In essence, Delta Plan is a multi-governmental framework, as visualized in Figure 22, applicable at all scales and based on three objectives with a long-term horizon (towards 2050):

1. Protecting against floods is not enough; risk reduction must be guaranteed in the future wherever they come from (sea, rivers, rainfall)
2. Securing freshwater supplies for population demand, agriculture, and industry
3. Responding to climate change through resilient spatial planning, i.e., transforming cities into impact-proof spaces

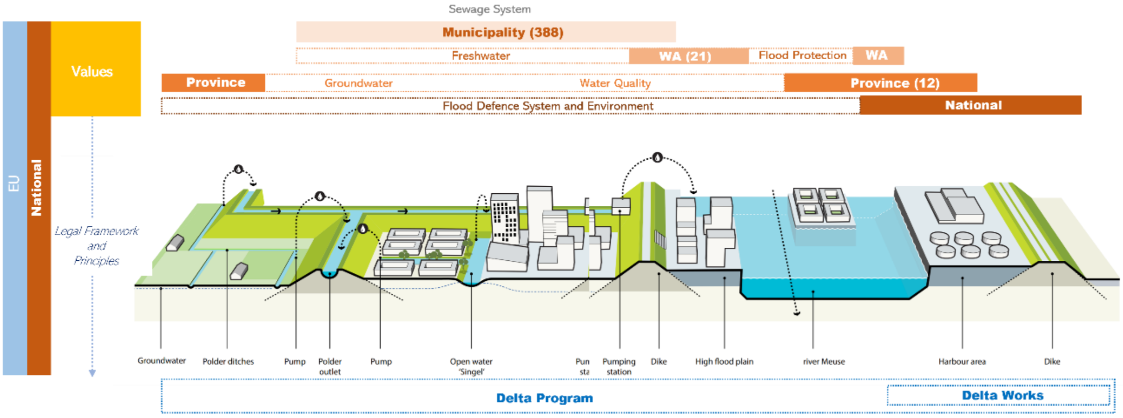


Figure 22: Multigovernmental framework in The Netherlands

Source: Created by author, adapted from OECD, 2014; DE URBANISTEN, 2016.

The Delta Plan at the macro scale establishes the need to align the country's policy to the legislation of the European Union of which they are regionally part, as well as the priority of managing border waters through participation in international river basin commissions. Internally, specific tasks are assigned to each level, central government, provinces, regional water authorities, and municipalities. At the national level, the focus is on coastal areas. Its mission is to protect against flooding due to sea-level rise. This aspect is being done with innovative projects. For example, the multifunctional dams provide protection and add other benefits such as providing recreational spaces for the population and increasing wildlife and biodiversity. On a regional scale and under the coordination of the various provinces, water authorities, and even private companies, their mission is to continue the flood protection work with greater emphasis on the banks of the many rivers and canals that cross the country. They also focus on securing freshwater sources for the population, agriculture, and industry and monitoring water quality. A Room for the River project is a clear example providing:

- sufficient space for when the river rises in the rainy season and a complete understanding of the water cycle,
- a better relationship between water and space, and
- protection of nearby cities from flooding (European Environment Agency, 2018).

At the municipal scale, its primary function is to ensure the decongestion of drainage systems in the face of increased rainfall and wastewater treatment. This effective combination of bottom-up and top-down processes in its design is indeed the basis for the success of the Delta Plan by ensuring the long-term ownership and commitment of all its stakeholders and the end-users (OECD, 2014). Cities like Rotterdam, beyond the large emblematic projects that have been implemented by the national government and even the international community, have opted to develop small-scale projects seeking to empower their population in the implementation of solutions. For instance, the Water Plazas and Multifunctional Roofs project absorb water like a sponge, functioning as catchment areas in rainy seasons and reducing water discharge into the drainage system. Nevertheless, they also work as public spaces to increase the sense of belonging of the neighborhood and even serve as areas to encourage urban agriculture in the neighbors (CLC, 2019).

3.1.2 Bridging Gaps

Another important aspect is the regulatory support required to manage any initiative at the governmental level properly. In this sense, the Delta Law also plays a leading role as it is the basis for implementing the Delta Plan. Although all the technical parameters are included in this policy at the national level, one of the most innovative aspects, as shown in Figure 23, is the inclusion of philosophical concepts applicable to all scales: Solidarity, Sustainability, and Flexibility.

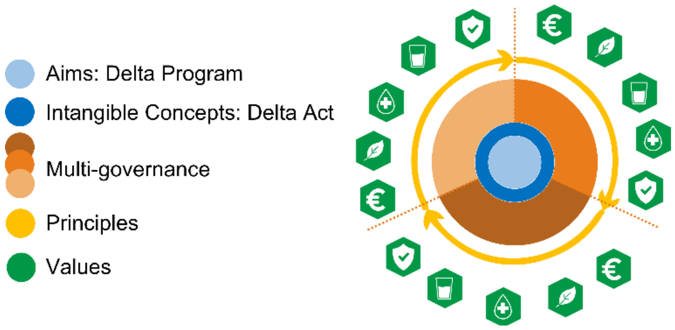


Figure 23: Delta Plan Conceptual Framework

Source: Created by author, adapted from Government of the Netherlands, 2015.

The first implies that solidarity must take precedence even when responsibilities are defined; this means mutual aid regardless of whether or not it is contemplated as the stakeholder's responsibility. The second is centered on the search for multiple sources of sustainable financing, understanding that water management is not only the government's responsibility and other private actors must join in, but also that these sources must be consistent with reducing climate change impacts. The third, Flexibility, essentially seeks water management that is flexible to change, understanding that climate change is unpredictable so that plans must be updated annually. Another essential aspect of the holistic vision of the Delta Plan is the principles and values that must accompany any project that is part of water management within the country. Firstly, understanding the complete water cycle, then improving the relationship between water and land, and thirdly, ensuring water quality and a harmonious relationship with the environment and ensuring the sustainability of the financial resources for its implementation (Slob and Bloemen, 2014).

Another essential aspect within the Delta Plan's regulatory framework is the interrelationship with other management spheres, such as spatial management. Establishing coherent relationships between water, land use, and spatial planning is one of the pillars of a water-sensitive approach. Spatial organization at an early stage plays an essential role in solving water challenges and increasing the harmony between planning and financing, seeking not to duplicate expenses or incur unforeseen ones. In the case of The Netherlands, the Delta Plan applies this connection to various areas of water management, emphasizing flood risk and water quality improvement. This progression has generated an inclusion of the Spatial Planning Regulation (Plan Act) and the Environment Act as essential requirements and an incentive program for its implementation to ensure that water resources are fully safeguarded (Government of the Netherlands, 2015). The multifunctional dike Katwijk ann See is a clear example. Although the primary function of the dams is protection, added values such as the creation of public spaces or the provision of services can be added to this formula. With the participation of local citizens, a series of high dikes covered with natural dunes were developed, which serve as areas for children and adults to enjoy and play. Together with the retailers, the project also attempts to solve the parking problem in this coastal area, creating a series of underground parking lots, as shown in Figure 24. Behind the cold concrete dikes, the project aims to improve the relationship between water and space.

Figure 24: Multifunctional dike Katwijk ann See

Source: ARCHELLO, 2019

- <u>Bridging financial gaps</u>

The range of threats to which water management in The Netherlands is exposed is innumerable, from natural to anthropogenic. This situation requires large amounts of money to be made available for its proper development. In 1998 the public budget for water management amounted to more than 3 billion euros (1% of national income), and direct taxes covered almost 70% of the funding from residents and companies (Van Steen and Pellenbarg, 2004). At present, more than 7 billion Euros are invested annually at different levels of government, the most significant contributors being the (Regional) Water Authorities with more than 2.8 billion Euros resulting from taxation and self-financing (OECD, 2020). Several mechanisms allow almost total economic autonomy (95%) on the part of the Water Authorities, among which "polluter pays," "user/beneficiary pays," and "interest pays."

Nevertheless, not all of them have been developed in the same way, the most important and recognized for its effectiveness and efficiency being the polluter pays. Under this principle, the water management system imposes taxes in the form of emission taxes, calculating their rates based on pollution indices according to the user's category: pollution tax for households or companies and wastewater treatment tax. While the primary function of taxation is to reduce overall pollution and protect the cleanliness of the water, it allows the creation of sufficient funds for the implementation of investment and maintenance projects on a regional scale (Van Steen and Pellenbarg, 2004).

- Bridging technical capacity gaps

The effective response to the challenges facing water management in The Netherlands relies heavily on its commitment to innovation in the construction and implementation of new and improved technologies and close linkages between the public, private, and research sectors. This approach is oriented towards the production of scientific research and the improvement of innovative capacity, essential to support informed decision-making. An example of this knowledge alliance is the Building with Nature project led by the private sector, research institutions, and public funding from the central government. The development of this concept attempts to establish innovative processes in harmony with nature and strengthen the technical and human capacity of professionals in the country. There is currently a network of more than 4 thousand water professionals (engineering, sanitation, environment, and governance fields) whose objective is to share knowledge and experiences, understanding this exchange as the basis for developing effective policies and implementing the most appropriate solutions (OECD, 2014).

- Bridging participation gaps

Water management in The Netherlands, as previously mentioned, went from a command-and-control approach to the current integrated and adaptive approach; however, in the face of this hybrid system, conflicts have shown hierarchical governance styles over the population, such as the case calamity polders. Rural areas were designated as flood zones to protect urban areas from flooding. However, the process did not consider the implications on the affected area's inhabitants, generating significant protests (Pahl-Wostl, 2019).

Although over the last few years, there have been advances in the involvement of end-users and the local population seeking to bridge the gaps. However, these are still more collaborative and informative than strictly participatory decision-making. From the informative perspective, the process began at the national level by implementing flood vulnerability warning systems. Later, as it evolved into a collaborative process, the population was involved in the design of water-sensitive projects, as in the Room for the River project. Although the first steps have been taken towards its implementation under the principle that the problem is everyone's problem and everyone must be part of the solution, it is still not robust enough as in other contexts. Cases such as Belgium or Singapore show that it is feasible to actively involve the population in preventive and educational actions. In the Belgian case, urban laboratories are used for collaborative work with stakeholders and the citizens seeking a better understanding of the water cycle and strong involvement of end-users and local citizens in decision making (BRIGAID, 2020). The case of Singapore, on the other hand, through a system of committed education, achieves uniform participation of the community in the decision-making of its ABC Program (Liao, 2019).

3.2 Adelaide (Australia): WSUD to reuse water

Australia, home of the WSUD, has low and variable precipitation levels throughout its territory. During the last few years, it has been facing the impacts of climate change, increasing 2.1 degrees above its annual average maximum temperature and reducing its average rainfall by up to 40%, going from 465.2mm to 277.6 millimeters per year in 2019. The country's urban population is growing, and 90% of its inhabitants are concentrated within a 100km radius of its coasts. According to the World Bank's development indicators, access to water and sanitation services in urban areas of Australia shows 100% coverage (excluding indigenous communities). However, the sum of climatic, geographic, demographic, and climate change impacts exert increasing pressure on water resources throughout the territory, especially in the capitals of the five states where 2/3 of the population is concentrated (Radcliffe and Page, 2020, p.19; World Bank, 2021). This situation has brought the need to reuse wastewater, an aspect of which Australia has already acquired knowledge throughout its history.

During the 1990s, a severe drought hit the country, and a change in the restrictions imposed on discharges from WWTPs promoted water recycling. The construction of water treatment infrastructure for indirect potable use and installing dual pipelines (potable, recycled water) increased throughout the country, with cities such as Sydney, Melbourne, Adelaide, and Perth installing desalination plants on their coastlines. Over the years, the costs associated with processing the water were not comparable to the use of catchment water, leading to the closure of the plants. However, this changed during the droughts of 2019. In the face of water scarcity, cities seek to diversify their water sources through indirect potable recycling schemes combined with the already known water-sensitive methods (Radcliffe and Page, 2020).

Another critical matter in Australia is related to the thermal comfort of its inhabitants in the face of heat island impacts, with the country suffering an increase in heatwave deaths in recent years. Studies suggest that WSUD, in combination with other approaches, is beneficial for restoring the natural water balance and supporting evapotranspiration and the irrigation of green areas driving evaporative cooling. However, the benefits of implementing these strategies in the face of microclimate variability in Australian cities are highly variable. In subtropical or tropical climate zones such as Brisbane and Darwin, while humid conditions decrease evaporative cooling, the provision of water for vegetation promotes shaded areas by reducing surface radiation temperature by up to 2 degrees. Conversely, the benefit may be more significant in more arid areas with a high concentration of urban population in the country, such as Adelaide (Coutts *et al.*, 2013, pp. 20-22). However, as Meerrow and Natarajan point out, and as shown in Table 3, the performance in these areas (arid or semi-arid) depends on the type of the green area to be implemented, being trees, vegetation, and permeable pavements the ones that show the most significant benefit compared to the need for cooling (Meerow, Natarajan and Krantz, 2021).

	Permeable Pavement	Stormwater Harvesting	Vegetation /Rock Swale	Bio-retention basin	Infiltration Trench	Trees	Vegetation	Green Infrastructure
Hydrological Performance	X			X	X	X		X
Water Quality		X	X					X
Urban Heat						X	X	
Air Quality	X					X		

Table 3: Effective Performance of green elements in semi-arid environments

Source: Created by author, adapted from Meerow, Natarajan, and Krantz, 2021.

3.2.1 The aridity of Adelaide

The conditions in the Greater Adelaide Region, where the Adelaide metropolitan area is located, are unique and arid, with seasonal rainfall and summers reaching 40 degrees Celsius for periods of up to 10 days. It also has the most extended consecutive dry periods of any capital city in the country, making it challenging to maintain vegetation systems, so it is necessary to consider an additional storage system to provide water during these periods. Since the 1990s, as previously mentioned, water-sensitive projects have been implemented with particular emphasis on wastewater treatment for irrigation and domestic services at various scales through conservation, collection, and reuse systems. Some clear examples are The Glenelg to Adelaide Pipeline (GAP) and Old Port Road Wetlands at the mesoscale and New Haven Village at the local scale. A relevant aspect of the strategy implemented in Adelaide is its adaptation to the conditions of the specific application site (they are not standardized to the whole region). The characteristics of the pollutants requiring treatment influence the selection of the type of treatment needed, while climatic and catchment conditions influence the hydrological design. In addition, as a national requirement, all measures provide for floodwater harvesting (Department of Planning and Local Government, 2009).

3.2.2 Meso to macro-scale: Glenelg to Adelaide Pipeline (GAP)

At mesoscale since 2008, Adelaide implemented the Glenelg to Adelaide Pipeline (GAP) project, a 50 km pipeline network supplying 3.8 GL of treated wastewater from domestic activities (toilets, sinks, drains) to irrigate public parks in the city center to ensure their resilience to the effects of droughts. For treatment, the network of pipes is connected to Glenelg's WWTP wastewater treatment plants. As shown in Figure 25, the process uses a mix of ultrafiltration membranes, ultraviolet disinfection, and chlorination to ensure that the water is safe for use (it has a higher salt content than drinking water) and meets quality standards. The GAP also shows other benefits, reduces dependence on the Murray River as a source of high-quality water supply for irrigation and reduces the discharge of nutrient-rich treated water into the gulf that affects seagrass meadows, provides healthier marine ecosystems,

Furthermore, it increases the quality of green spaces valued by the community. Another significant benefit is the buffering of heat island effects; according to aerial thermal imagery analysis, irrigated vegetation's cooling effect can be up to 25 degrees cooler than gray areas in the city's CBD (CRCWSC, 2020, pp.1-3).

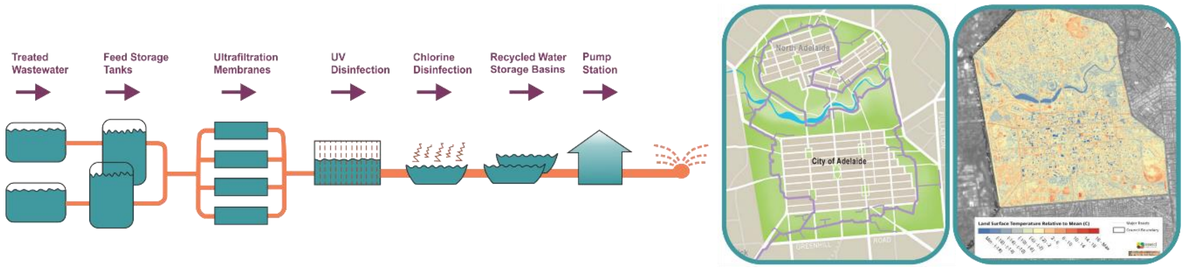


Figure 25: Glenelg to Adelaide Pipeline (GAP) process

Source: Government of South Australia, 2017

It is essential to highlight that one of the missing components of the project is the aesthetic value of a water-sensitive project since the pipeline network is underground. However, some key aspects stand out in the project, such as the need to involve and educate the community and other stakeholders with scientifically-based information due to concerns about water quality. This aspect must be complemented with periodic controls of soil, plant, and aquifer quality due to the high concentration of salts in the recycled water. Other elements such as the articulated work between the various public-private stakeholders, especially to cope with the first investment and the direct benefit to landowners by offering an option to significantly reduce their irrigation costs (compared to drinking water), are other lessons that can be drawn from the Glenelg to Adelaide Pipeline (CRCWSC, 2020, pp. 4-5). The project plans to continue to grow as it seeks to adapt to large parts of the territory.

3.2.3 Meso-scale: El Old Port Road Wetland

Constructed (or artificial) wetlands have emerged as a viable option for wastewater treatment and other environmental problems with a high landscape component. The Old Port Road Wetland, a meso-scale initiative, is the first stage of a larger scale project developed west of Adelaide. Through 11ha of constructed wetlands, as shown in Figure 26, it collects rainwater, treats, stores, and distributes it for irrigation of landscaped areas, toilet flushing, and ornamental pond operations. The system includes 36 km of pipelines. The water is first collected from rainwater that initially discharged and polluted the Torrens River (presence of oils and other pollutants present in urban pavements) and from water that drains into nearby catchment basins. In the second stage, in addition to receiving treatment in the artificial wetlands, the water is injected into the local aquifer during wet seasons and then extracted and used during dry seasons. In the third stage, the treated non-potable water is distributed to the surrounding suburbs allowing a reduction in potable water consumption by 555 milliliters annually and preventing the entry of 1704 m/l yearly into the Gulf. With the following stages of the project still under development, the aim is to increase the recovery of 2,400 m/l of stormwater each year and continue raising awareness and changing perceptions about water sustainability (CRCWSC, 2019).

In the context of wetlands, recent studies warn of the need for aquatic invertebrates to play a predatory role in controlling mosquito larvae production. If this natural food chain - predator/prey - is preserved in wetlands, health risks are minimal. Another aspect the study highlights is the benefits of artificial wetlands as multifunctional ecological systems (promoting wildlife habitat and passive recreational activities) versus tertiary concrete treatment plants, even though the former require more land area. In addition, due to its capacity to eliminate pathogenic microorganisms, it can be used for the irrigation of green spaces, reducing costs compared to secondary or tertiary effluents. In the case of the benefits compared to natural wetlands, Greenway points out that many natural wetlands are only flooded during certain seasons, forcing wildlife to seek alternative refuges during the dry seasons. In contrast, artificial wetlands are not variable in their sources, providing secure habitats and restoring natural wetlands with treated water (Greenway, 2005).

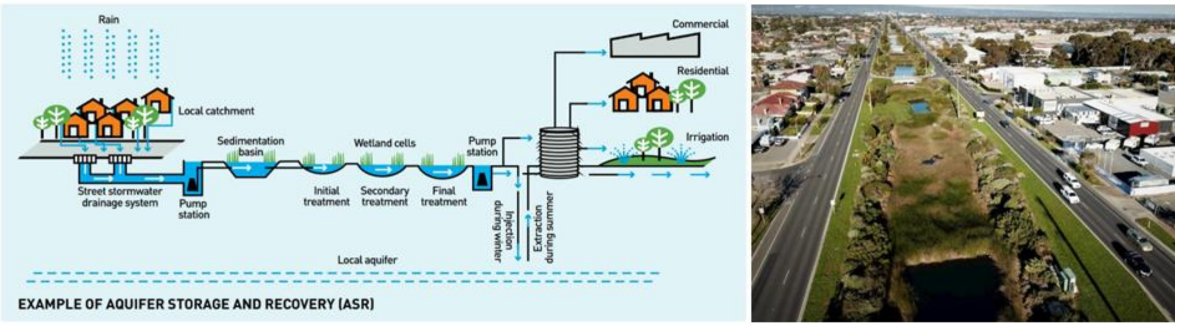


Figure 26: The Old Port Road Wetland

Source: CRCWSC, 2019; DESIGN FLOW, 2020

3.2.4 Micro-scale: New Haven Village

At the micro (or community) scale, a project in Adelaide called New Haven Village has been working since the 1990s to demystify the use of recycled water. New Haven Village is a suburb located 20 km northeast of the city; the system contemplates collecting rainwater and greywater and its subsequent reuse after prior treatment. Much of the stormwater runoff is created by roads and paved areas, and in the case of New Haven Village, the width was reduced from 12.4 meters to 6.8 meters, limiting impervious ground surfaces by default. In addition, the roofs include conduits that discharge into drains, which through a system of grates trap solid waste before it enters the system. In this first stage, the water is discharged into a 40,000-liter tank, a resource that is stored only during the wet season, allowing irrigation of the neighborhood's sports areas. During the second stage (treatment), the collected water is pumped to a conventional station, filtered with sand and ultraviolet light, and stored in underground concrete tanks. An innovative solution was found to the usual sludge problem: it is used to make bricks. Moreover, some houses in the neighborhood have even been built with it as a base. After treatment and storage, the water passes through an underground network to feed the irrigation systems of public and private green areas and the cisterns of residential toilets (Radcliffe and Page, 2020).

According to what suggested by authors such as Radcliffe and Page (2020) and Beza, Zeunert, and Hanson (2018), the implementation at this micro-scale in Australia is sometimes more feasible and cost-effective to work ensuring better functioning of water sensitive strategies (Beza, Zeunert and Hanson, 2018; Radcliffe and Page, 2020). Another essential aspect that revolves around the reuse of wastewater is analyzing why the population develops rejection of its use. The truth is that this aspect has not been deeply explored in the world, and consequently, there are few standardized strategies to overcome it. In the specific case of New Village, a survey shows that 95% do not encounter problems with the collection, treatment, and subsequent reuse of water for domestic sanitation services or in the irrigation of private or public green areas. However, they did mention occasional problems with toilet cisterns related to foul odors and cloudy colors that should be solved. The results also show a progressive change by 35% of the residents in their irrigation systems, moving from surface systems (micro sprinklers) to underground systems, due to constant obstructions in the canals due to water with a higher amount of salts (Coutts *et al.*, 2013). In the case of Queensland, another Australian city, studies suggest that the communication difficulties experienced are due to the absence of public consultation, highlighting that the inclusion of this component when designing a water source diversification strategy is of utmost importance (Radcliffe and Page, 2020, p.37).

Other studies conducted in Nigeria (2020) suggest that the success of wastewater reuse from the aesthetic aspect is based on its ability to be integrated into the planning of the environment, highlighting the need for elements that enhance the site's landscape. From the social aspect, the respondents revealed that although they appreciate the economic and environmental importance of treated wastewater, they prefer little contact with the project for health reasons. This aspect is due primarily to a lack of awareness of water scarcity and professional endorsements from the health and education fields about the actual water quality conditions. While statements can be drawn from the study, they merit further comparative analysis with other settings and realities (Akpan, Omole, and Bassey, 2020).

From a general perspective, meso- and micro-scale initiatives add to Adelaide's efforts to move towards a Water Sensitive City. Although there are no projects implemented at the macro scale covering the entire territory or its relationship with other nearby regions (regional scale), it is certain that during 2020 the city has managed to put on paper an integrating Vision to 2067. This document compiles the city's initial analysis, the actions to be taken in the future, and the different scenarios that the vision will have to face (Gunn *et al.*, 2017). However, as highlighted by Beza, Zeunert, and Hanson (2018), in the Australian context to take the next step in the framework of sustainable development and transition to a WSC, more critical challenges need to be addressed: first, the decoupling between urban and territorial planning and the implementation of water measures, and second, the fragmentation in the decision-making institutions (Beza, Zeunert and Hanson, 2018).

Regarding the first aspect, there is a need to establish articulated strategies at all scales to achieve significant effects. Although each scale responds to specific objectives and employs different tools and techniques, applying them together ensures sustainability (Carmon and Shamir, 2010). About institutional fragmentation, the authors highlight the need to create a new level at the national scale to insert through it cross-cutting WSUD policies and standards. Thus, the country will foster rapid adoption and promote positive environmental outcomes uniformly across its territory, as in the Netherlands (Beza, Zeunert, and Hanson, 2018).

The National Water Initiative (NWI) is a national plan for water reform agreed in 2004 by all Australian governments in coordination with private stakeholders. It is the first significant step in establishing a timeline of reforms to develop comprehensive water plans under a single common goal and oversight and monitoring actions for the commitments made. Nevertheless, roles and responsibilities are still unclear beyond the commits (Australian Government, 2014).

Summary of the Chapter

The transition to a WSC involves facing several practical challenges in the process. Over the last few years, many urban environments in this evolution have adapted the water-sensitive approach recognizing the need to bridge gaps in both management and practice. Their knowledge and understanding could better outline the ideal, though not exclusive, paths to follow in order to avoid undesired scenarios. In that sense, throughout the chapter, the review of best practices allows answering the second research sub-question, What can be learned from existing Water Sensitive Best Practices to better elaborate a WSUD framework?:

The WSUD approach requires bridging functional, spatial, and participatory gaps to apply a multiscale model: Cases such as The Netherlands show that the challenges facing urban environments today in the water framework require a governance system with a closely linked government, civil society organizations, and business community. It also shows that decentralization in governance should be at the functional level and from the territorial aspect relating all scales with straightforward tasks and functions at both horizontal and vertical levels that fulfill the common long-term objective. To this end, the practice highlights the importance of bridging regulatory, technical, economic, and spatial gaps, pillars that the theory of the water-sensitive approach proposes as necessary. Thus, combining these components can be the basis for a comprehensive shift towards a multi-governance model. However, the application and success of this system rely on the government's ability to be flexible, sustainable, supportive, and participatory, understanding participation as the promotion of the involvement in decision making of end-users and the local population. Nevertheless, this is an aspect that even the hybrid system of The Netherlands has shown hierarchical nuances that require attention.

In semi-arid environments, wastewater recycling through artificial wetlands provides multiple benefits: The literature review also shows that in semi-arid environments such as Adelaide, wastewater recycling offers a compelling alternative source to address water scarcity through strategies to improve climatic comfort and meet irrigation water demand. Some water conservation, harvesting, and reuse projects at different scales, mainly using constructed wetlands, have been developed over the last few years. The city system recognizes the multiple benefits of artificial wetlands over other traditional schemes for integrated wastewater treatment management and ecosystem balance. They treat by eliminating pathogenic microorganisms, distribute for non-potable consumptive uses, and are a refuge for wildlife, improving the surrounding landscape.

The micro-scale to better manage wastewater reuse system: The city also recognizes the social profitability and better functioning of water-sensitive strategies at the community level. Articulated methods of water collection, storage, treatment, and reuse allow for the irrigation of green areas (public and private) and to feed cisterns of residential toilets after a process of filtration with sand and ultraviolet light. The experience also reveals the need to integrate water reuse systems into the urban environment through aesthetic strategies with social and recreational value. They also require strengthening the communication and participation systems with the community by establishing public consultations and showing professional endorsements from the health and education fields and a constant and transparent water quality monitoring system. However, the applicability and potential of these initiatives imply having governance systems with clear roles and rules, an aspect that is not characteristic of developing environments where the capacity for their adoption is still limited. Furthermore, the conditions found in the case of Adelaide show a 100% coverage level of the city's water and sanitation services, so that wastewater reuse has a non-potable consumptive approach, contrary to the need that is required in developing environments with unmet basic water needs.

Chapter 4: Metropolitan Lima (ML)

This chapter will analyze the inherent characteristics of the Lima metropolitan area in the framework of water management in three stages. The first intention of the chapter will be to understand the main reasons that have led Lima to a situation of water vulnerability, and it will analyze the role of the existing urban ecological network and its blue, green, and gray components that compose it. It will also explore water governance in the city and its relationship with the different spheres (national, regional, metropolitan, and local). It will highlight the regulatory framework and public policies and the actors involved in current water management. Questions such as What are the characteristics of Blue and Green Infrastructure (BGI) in Metropolitan Lima? Moreover, what is Lima's Governance capacity to address water challenges? will seek to be answered. A second intention will be to obtain relevant quantitative indicators on water capacity by analyzing natural and anthropogenic sources through the Urban Metabolism approach. The analysis will focus on water flows in and out of the city and determine the resource's efficiency through indicators. This section will seek to answer: Which water flow has the most significant potential for improvement in the water system of Metropolitan Lima? Finally, the unit's conclusions will be summarized by answering the question: What are the main socio, ecological and spatial drivers of Metropolitan Lima's water scarcity and water insecurity? It will discuss the research findings from the literature review and best practices.

Metropolitan Lima (ML)

Lima is the capital of Peru, and it is the political, economic, and cultural center of the country, with an extension of 82 km from north to south. The city is located in the central-western part of the Peruvian territory being part of the Sechura desert. Territorially, it compromises a very wide continental and maritime space. Politically, the Metropolitan area of Lima (ML) is an urban agglomeration formed by the provinces of Lima and Callao, spatially connected through the urban fabric as visualized in Figure 27, but with different political administrations (Eisenberg *et al.*, 2013). After Cairo (Egypt), Metropolitan Lima is the second-largest city globally, located in a desert. One of its main environmental constraints is its scarcity of natural water due to particular geographic and climatic characteristics (AQUAFONDO, 2015). Hydrographically, the city is situated in the lower areas of the Chillon, Rimac, and Lurin basins (CHIRILU), three rivers of the same name supply the city with water resources.

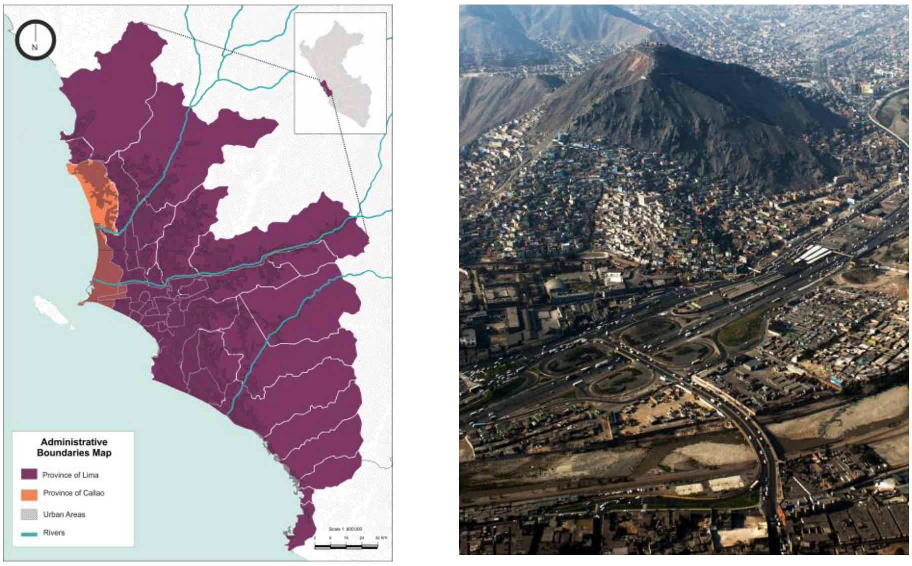


Figure 27: Metropolitan Lima (ML)

Source: Created by author, adapted from MML, 2014; AQUAFONDO, 2015.

4.1 Times of water harmony

Throughout history, proximity to a water source has been an essential point for the settlement of civilizations globally. Lima is based on a pre-Hispanic water legacy marked by harmony with the environment and the vision of water as a vital resource. Hence the importance of quickly reviewing its most essential components.

4.1.1 Network of canals

The first evidence of the relationship between the territory of Lima and water dates back to between 1500 B.C. and 100 A.D. when the inhabitants of the Rimac Valley used canals to transport water from the river of the same name to distant places to irrigate cultivated areas. Thus, the Surco, La Legua, and Huatica canals appear next to U-shaped temples like the Garay, Salinas, and La Florida. However, even the hydraulic system was simple and not very complex. It was between 200 A.D. and 650 A.D., and with the arrival of the so-called Lima Society that the system was expanded, and a vast network of hierarchically distributed canals was built throughout the territory (primary and secondary canals) and interconnected to the wetlands existing at the time, as shown in Figure 28. Around 900 A.D., the network system grew with the Ate Canal and the Magdalena Canal, allowing settlers to dwell in the middle and lower areas of the valley, which today are known as the Maranga neighborhoods. Between 900 AD and 1450 AD, with the arrival of the *Curacazgos*[1] of the Lordship of *Ychma*[2], the crop irrigation system was expanded with the Huadca canal, and the first reservoirs appeared. This new reservoir technology implementation and the installation of water intakes allowed the settlers more excellent and better water management to increase agricultural production (Chávez, 2010; ANA, 2016).

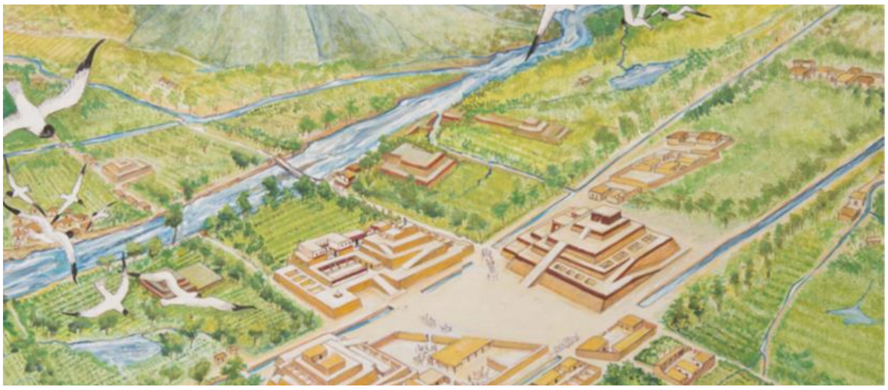


Figure 28: The water as a vital resource during the Pre-Hispanic period

Source: ANA, 2016

Nevertheless, it also allowed the use of water as an element of power to negotiate within the Lordship. During times of natural scarcity, it allowed to rationalize it, and during seasons of abundance, it allowed to reduce conflicts. To access it, the leaders of each Curacazgo and their people had to manage support tasks such as cleaning the canal or other collaborative

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[1] ***Curacazgo:*** *System of organization of the different social and ethnic groups of the coastal zone of Peru who was entrusted with the care of a part of the canalization System* (Agurto, 1984).

[2] ***Ychma:*** *Lordship controlled a group of Curacazgos in the coastal zone* (Agurto, 1984).

work. With the arrival of the Incas between 1450 A.D. and 1533 A.D., the use of water as an element of power even led to the creation of marriage alliances between Curacazgos. This aspect was with the sole purpose of preserving control of fertile lands. Indeed, corn was the star product of the time, and this control of the territory and water resources allowed its cultivation and exchange with other parts of the empire (ANA, 2016).

The fall of the empire came with the colonization of the Spaniards. Thus the power exercised over water in Lima changed its hue. The hydraulic system of canals in the Rimac Valley was affected by constructing houses and public buildings. Another aspect that added to the weakening of the system was the dismantling of the Curacazgos. As a result, the maintenance of the canals previously entrusted to this population was lost. The harmony with the valley was also lost as cultivated areas were eliminated for the construction of irrigation ditches that brought water to urban areas, as shown in Figure 29, but at the same time dumped wastewater into the Rimac River. Water supply throughout the territory could no longer be direct (taking water from canals and rivers) due to the appearance of diseases caused by environmental contamination (ANA, 2016).

Figure 29: Open irrigation ditches during the Colonial period

Source: ANA, 2016

Furthermore, the river was used as a physical element to divide the population socially. On the one hand, there were the neighborhoods of the aristocracy (Cercado de Lima), and on the other, the Indian communities. During the republican and modern periods, the urban expansion continued to reduce the hydraulic development and the loss of identity of the rivers that cross the city. At present, the canal system still exists. However, a large part of the original infrastructure has changed its use and today serves to irrigate municipal green areas, an aspect that will be analyzed later (Chávez, 2010; ANA, 2016). The Rimac and Chillon rivers are considered physical elements that divide the city and are commonly referred to by the population as "Lima's backyard" (ANA, 2013). They require a reincorporation into the urban fabric for its landscape value and a recognition of its water value by the authorities and the population for being the primary water source that supplies the city.

4.1.2 The Amunas

The *Amunas* are another pre-Hispanic water infrastructure system that should be mentioned. Amuna in Quechua (the native language of the Andes) means to retain. In essence, and as shown in Figure 30, the amunas are canals built with impermeable stone over permeable terrain that allows for artificial recharge of the aquifer during rainy seasons, which is usually known as water harvesting. During dry or low water seasons, the communities can harvest and use the water through *Puquiales* [3] or *Ojos de agua* (water eyes). This system is originally from the high Andean zones of Peru. However, in the high zones of the coastal basin, there is a network of canals that, although they were thought to be forgotten in history, have been very useful nowadays to the communities that inhabit the rural areas of the Lima Region. Although the amunas are located outside the urban system of ML, they are within the basin that supplies the city, so their recovery and incorporation into the system are transcendental. According to the latest studies, 1 km of Amuna provides a little more than 225 thousand cubic meters (m^3) of water per year. Nowadays, more than 17.7 km of amunas have been recovered, contributing more than 4 million m^3 to the Rimac and Lurin river basins. Nevertheless, more than 62 km of amunas need to be recovered (AQUAFONDO, 2020).

Figure 30: Amunas

Source: AQUAFONDO, 2020

Throughout Lima's water history, poor management decisions and the neglect of ancestral systems that maintained the balance in the Lima valley have impacted the city's inhabitants and ecological environment. The identification, recognition, and, above all, appreciation of local practices that were successful in the past is an essential element in the proper management of water resources in the watersheds. Experiences in international environments, such as Chile and Ecuador in their quest to revalue ancestral hydraulic engineering, can be helpful for an eventual proposal (AQUAFONDO, 2020).

4.2 Living in the Desert: Population Growth in Metropolitan Lima

An aspect that exacerbates the water crisis in ML, as in many cities worldwide, is the rapid urban growth; thus, since the 20th century, the population of Lima has expanded at an accelerated rate, as shown in Figure 31. By the mid-1920s, the city was losing its traditional image as a colonial and republican city and gave way to first demographic growth, occupying the valley surrounding the city and drastically changing the urban landscape (MML, 2014). Subsequently, the beginning of the 1940s brought with it a wave of transformations not only from the economic aspect with the promotion of industrialization, the consolidation of a productive exporting structure, and the improvement of job opportunities but also with the State's attempts to modernize the country with the construction of more and new highways.

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[3] ***Puquiales or puquios:*** *Source of water or underground springs that supply water after up to three months of being harvested* (Ponce-Vega, 2015).

Until that time, Peru was primarily rural, and only 35% of the population lived on the coast. However, employment, education, and health improvements were concentrated in the coastal areas. In this context of economic boom, there was an increase in the migratory processes from the highlands to the coast (Matos Mar, 1986).

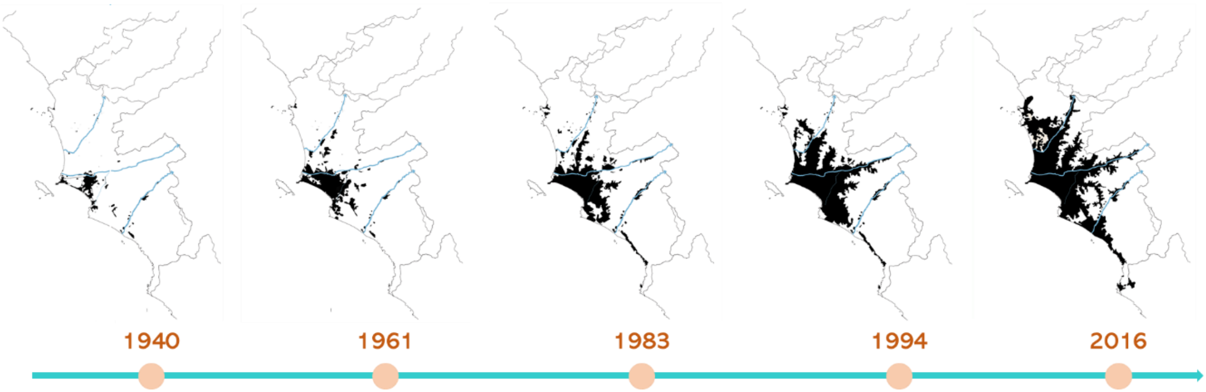

Figure 31: Urban growth in Lima

Source: Created by author, adapted from MML, 2014

As the author Sharif S. Kahatt states in his book Constructed Utopias, the 1940 census was the turning point in the city's demography, bringing with it urban conflicts that have characterized the city's history. The population in 1940 was 650,000 inhabitants (3 times more than in 1920), and 46% came from the provinces. Although migration from the countryside to the city was a phenomenon that occurred in several countries in the region, in the case of Lima, the industrialization process that provided job security and resources to adapt to the city was not at par. Within this context, thousands of migrants faced the need for housing and settled in the city's peri-urban areas, giving rise to *barriadas*[4] or informal settlements. By the end of the decade, data showed that the situation had worsened significantly. In 1948, estimates showed that 83% of Lima's population lived in poor conditions and could not meet basic needs such as housing and much less access to water and sanitation services (Kahatt, 2015). During the 1960s, the second most crucial population growth occurred, reinforcing the centralist approach offered by the capital, which could not still meet the needs of the masses for different reasons. More recently, during the 1980s, there was also a third increase in migration rates to Lima, mainly due to the expulsion of the rural population escaping the violence in the Andean region. Thus, as shown in Figure 32, in only 30 years, the urban area has increased by approximately 87% (from 387.8 km² to 726.2 km²), with the significant expansion in desert areas along the coast, followed by agricultural areas. Irrigated areas have been urbanized, causing these hydraulic sectors to decrease by about 74 km², resulting in a change in water use.

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[4] ***Barriada:*** *The term "barriada" refers, as stated by author David Collier, to residential communities, many times illegally created, made up of low-income families who, for the most part, have personally built their own homes. Later, during the military period in Peru, this term changed to "Pueblos Jóvenes" (Young Towns) (Collier, 1978).*

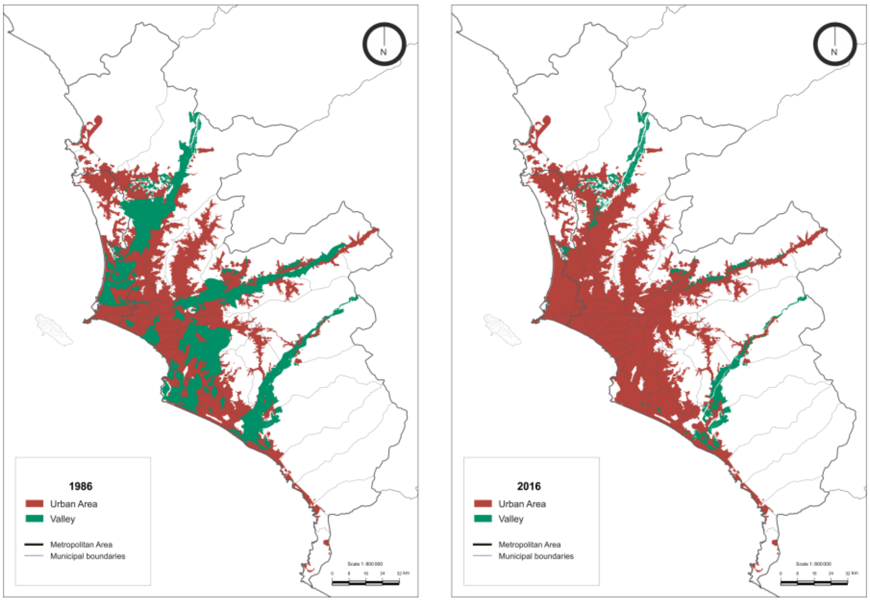


Figure 32: Land-use change in Lima over the last 30 years

Source: Created by author, adapted from MML, 2014; ANA and GIZ, 2018.

Today Lima hosts 10.5 million inhabitants, making it the first megacity in the country, and stands out for its multiculturalism, hosting people from different parts of the country. The city, which represents only 0.2% of the national territory and 6.6% of the department of Lima, is home to 32.3% of the national population, and this number will keep growing (Eisenberg *et al*., 2013; CPI, 2019, pp.7-8). Projections stipulate that over the next 15 years, the population will grow at an annual rate of 1.35%, reaching 13.2 million inhabitants by 2035, as shown in Figure 33. They also offer a very variable growth trend throughout the territory. While districts located in the last agricultural valley of the city will grow up to 9 times their current population, other communities located in the southern will maintain meager rates. Nevertheless, what is certain is that the population growth trend increases not only the need for urban spaces above the agricultural valley but also increases the population's water demand by 40%, representing a challenge for integrated water resources management (MML, 2014, pp. 227-228; INEI, 2020b; Stakeholders, 2020).

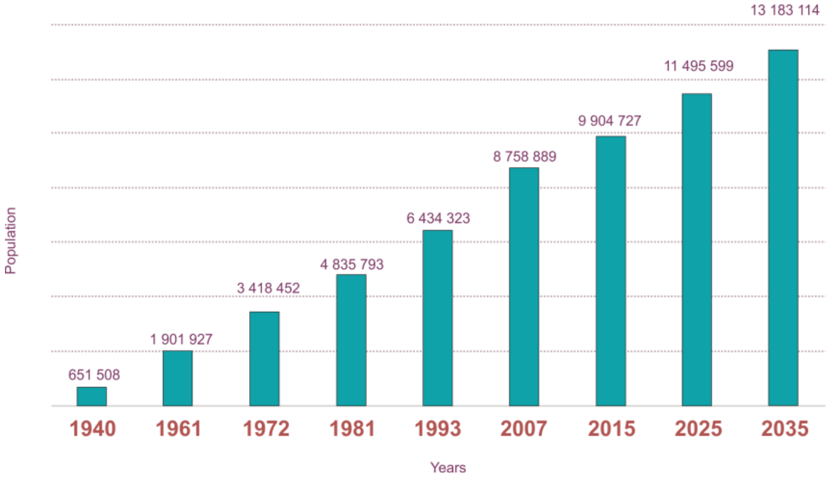


Figure 33: Lima's population growth from 1940 to 2035

Source: Created by author, adapted from MML, 2014; INEI, 2020b

According to a study carried out by AQUAFONDO using the Falkenmark indicator, Lima currently has a water scarcity situation of only 125 m³ per capita, four times lower than the absolute scarcity index. The results also show that the consequences of an even more profound water crisis would be severe. The city and the main economic center of the country would face losses of 9 billion dollars, and more than 652,000 jobs are at high risk, i.e., 43% of the economically active population today (AQUAFONDO, 2016).

4.2.1 Heterogeneous distribution

As previously mentioned, the city's growth, based on the demographic explosion of the last 80 years, has engendered formal and non-formal urban expansion processes. Nowadays, the population is distributed heterogeneously within 49 districts; 43 belong to the Province of Lima and 6 to the Constitutional Province of Callao. In addition, these districts make up five sub-centers with different socio-economic and geographic characteristics as shown in Figure 34: (1) Lima Centro (Center) as a traditional area of the city, geographically flat, and where most of the middle and upper classes live and where jobs and services are concentrated; (2) Lima Norte (North); (3) Lima Sur (South); (4) Lima Este (East) sub-centers located in the peripheral zone as a result of the process of consolidation of informal settlements and housing more than two-thirds of the population in geographically hillside areas, and (5) Callao as a coastal sub-center with mostly industrial overtones (Eisenberg *et al.*, 2013; Almaaroufi *et al.*, 2019).

The heterogeneity of population distribution throughout the city is reflected in the contrasting population density across the different sub-centers, an aspect closely linked to socio-economic conditions. In central Lima, districts such as San Isidro and Miraflores have relatively low densities. In contrast, the population density in San Juan de Lurigancho in eastern Lima, associated with peri-urban areas, has more than 300 inhabitants per hectare (MML, 2014, pp. 220-222). These city areas are a crucial element of the lack of access to water, usually, because the water network after the territory is informally settled and on steep slopes is often complicated and costly. Indeed, this gap must be covered and deserves prioritization before an eventual water-sensitive strategy (Burg *et al.*, 2021).

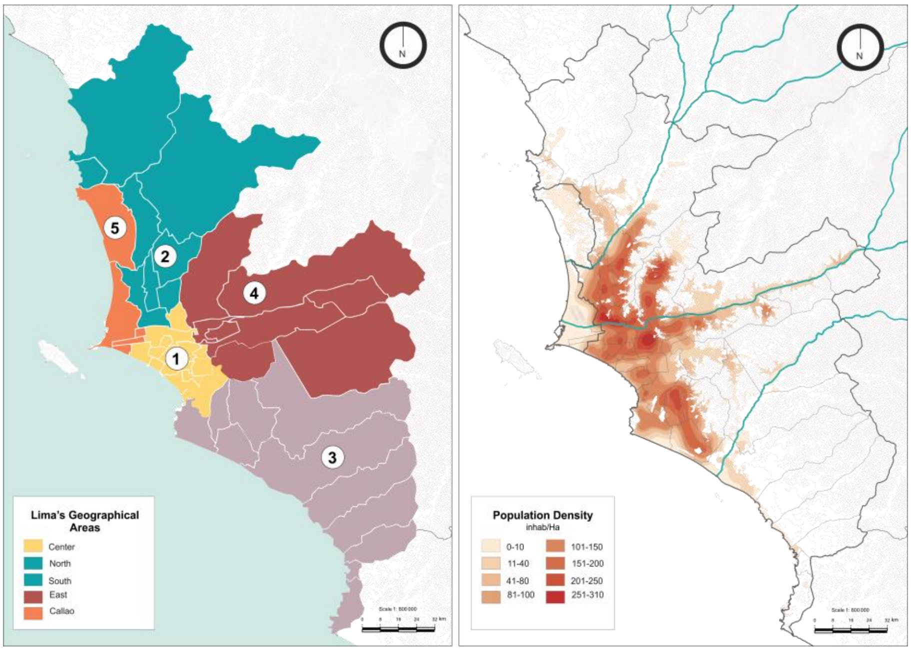


Figure 34: Sub-centers and population density in ML

Source: Created by author, adapted from MML, 2014; Eisenberg *et al.*, 2013.

4.2.2 Access to Basic Water Services

In Peru, access to drinking water and sanitation services is recognized as a constitutional right. However, the numbers are alarming; more than 23% of the rural population does not have the services. In ML, the magnitude is lower, although still worrisome (INEI, 2020c). Drinking water service coverage in the city is 96%; however, due to the irregularity of the surface water sources that supply the city (rivers) and the low water levels that characterize Lima's system, drinking water service is only available 21 hours/day. On the other hand, sewerage service coverage is 91% of the population served. The remainder of the population does not have household connections, so they have latrines. Coverage alone does not fully reflect inequalities; in the case of Lima, disparities are evident in the levels of accessibility from a spatial perspective, as mentioned before. At the territorial level, the city is stratified from an urban, economic, and social development perspective. In effect, the population with greater purchasing power occupies the central and consolidated areas with greater access to basic services and equipment, transportation, and higher quality of life standards.

On the other hand, the peri-urban areas are inhabited by the population with fewer resources and limited access to basic needs, as shown in Figure 35 (MML, 2014, p. 263). Approximately 1.5 million inhabitants do not have access to either of the two services, and most of them live in areas with medium or steep slopes. Districts such as Carabayllo, Puente Piedra, Santa Rosa, and Ancon in the north, San Juan de Lurigancho, Ate in the east, and Lurin and Pachamac in the south concentrate the majority of the lack of access to water and sewage services (MML, 2014, pp. 773-774).

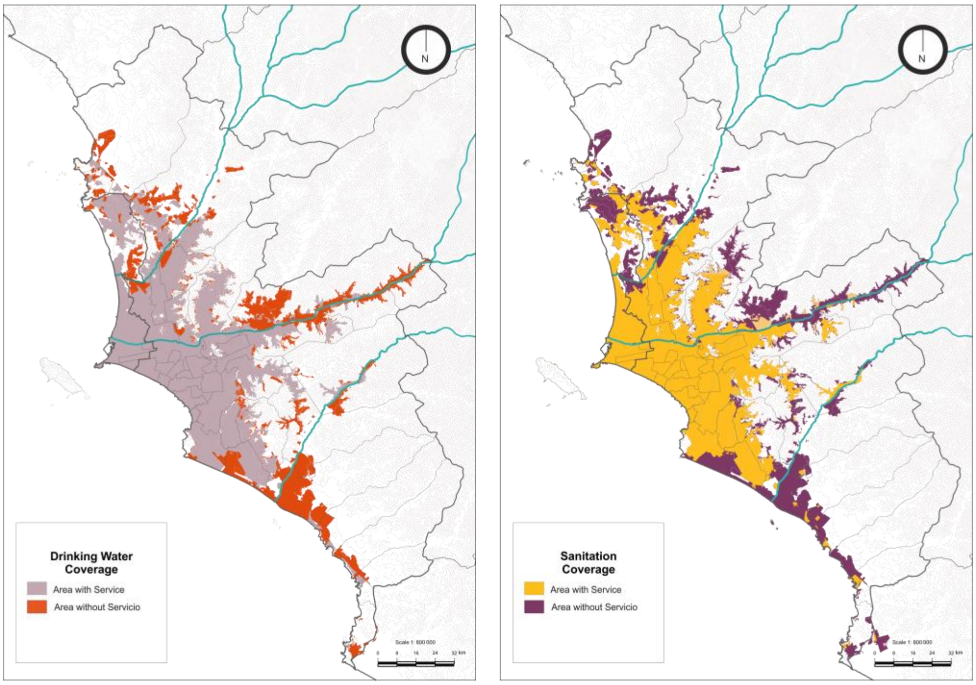


Figure 35: Drinking-Water and Sanitation Coverage in ML

Source: Created by author, adapted from MML, 2014; INEI, 2020c

The disparity in access to water is also measured in monetary costs. While some people have access to drinking water by paying a regulated monthly rate to a company, the majority of the population that lacks the service pays up to 10 times the cost per cubic meter to a tanker truck without sanitary controls and receiving water of dubious origin or from a clandestine underground well. According to research conducted by Ziegler and Morales in 2020, water tankers receive water at the cost of $0.16 (plus taxes) per cubic meter, which they resell at $4.9, 30 times higher than the original price. This price represents approximately 6% of the monthly income of a citizen living in poverty, which is well above the UN recommendation that no more than 3% of a household's income should be spent on drinking water (Ziegler and Morales, 2020). The cost also transcends to other areas as long periods of time are spent every three or four days transporting the cylinders of water from the unloading point of the truck at the bottom of the hillside to the house, taking time away from their daily tasks. Another aspect to consider is that the load is usually absorbed by women and children (Mervin, 2015). This situation is far from what is established by the World Health Organization (WHO). It considers that distribution systems should ensure that water suitable for human consumption is available so that people do not have to travel more than one kilometer from where they will use the water. Moreover, the collection time should not exceed 30 minutes (UN, 2011, p.5).

The magnitude of the challenges and needs faced in peri-urban areas leads the inhabitants to form community networks; thus, social cohesion arises in search of improvement. The Neighborhood Committees, Vasos de Leche, Community Kitchens (Comedores Populares) were born within that scenario, among many others. Since the 1960s, social organizations in the peri-urban areas of Lima have been fighting for urban consolidation, access to property, and essential services. During the last decades, they have been involved in mafias and clientelistic ties with government entities that only seek their vote in the face of false promises to meet the population's needs. Nevertheless, significant social capital within these organizations, which aim to improve or complete basic services such as water and sanitation networks, could be used in state-community relations (Torres, 2018, pp. 147-148).

4.2.3 Water Consumption

Another aspect established by the World Health Organization (WHO) is using 100 liters of water per day to optimally meet basic needs (Howard, Bartram, and WHO, 2003). On average, the daily per capita consumption in ML is 254 liters, one of the highest in the region, behind only Buenos Aires (336 l/cap/d) and well above the 176 l/cap/d consumption in Santiago de Chile (Marticorena, 2020; IWA, 2021). In other latitudes, cities such as Barcelona or London, consumption is in the order of 110 l/cap/d and 158 l/cap/d respectively and with very homogeneous patterns throughout their territories (MML, 2014, p. 774). Nevertheless, in this aspect, there is also a considerable disparity in Lima, in districts with higher purchasing power (San Isidro, Miraflores, La Molina, or San Borja), consumption ranges between 253 and 477 liters per person per day (400% more than recommended). In comparison, it is 16 to 41 liters per person in districts with lower purchasing power per day, as shown in Figure 36 (AQUAFONDO, 2016; EC-El Comercio, 2018b). In addition to those previously mentioned, possible reasons for this inequity could be the age of the primary network and constant leaks in the system, and a weak water culture on the part of the population, which adds significant stress to meet Metropolitan Lima's water demand. To better understand, a quantitative analysis of the existing supply and demand in the city and the primary sources of supply, wastewater collection, treatment, and recycling in the city will be analyzed in the UWMB section of the chapter.

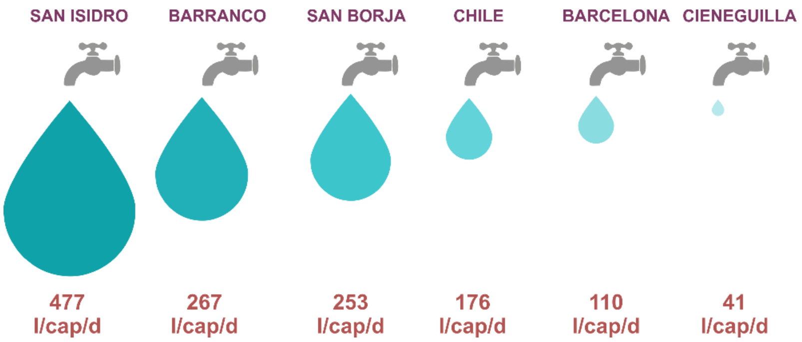


Figure 36: Water consumption in ML

Source: Created by author, adapted from AQUAFONDO, 2016; EC-El Comercio, 2018b; MML, 2014

4.3 Biophysical matrix and ecological structure of ML

The correct management of urban environments implies taking into account non-predictable elements that are difficult to modify. Indeed, the biophysical matrix is the set of abiotic and biotic components that make up the spatial and primary support. Bioclimatic, geomorphological, topographic, and ecosystemic conditions must be analyzed to reduce dysfunctional effects in the future. The development of this section is an attempt to understand the inherent elements that shape the city and answer the research question, What are the characteristics of Blue and Green Infrastructure (BGI) in Metropolitan Lima? ML occupies 281,926.7 hectares in territorial terms, compromising multiple interrelated components such as the urban area, coastline, wetlands, rivers, valleys, and coastal hills, as shown in Table 4 (MML, 2014, pp.120-121).

	Components	**Percentage (%)**	**Hectares (Ha)**
Lima	Coastline	0.9	2,527.0
	Islands	0.7	1,843.7
	Wetlands	0.2	593.7
	Valleys	3.9	11,099.0
	Rivers	0.2	765.0
	Coastal Hills	27.1	76,380.0
	Arid mountains	27.1	76,421.0
	Ravines	2.4	6,885.0
	Arid Pampas	5.1	14,275.0
	Urban Hills	0.5	1,521.0
	Urban Area	32	89,617.0
Total		**100%**	**281,926.7**

Table 4: Biophysical matrix and ecological structure of ML

Source: Created by author, adapted from MML, 2014

4.3.1 Geomorphology

Geomorphologically, ML is located on the Peruvian coast, which runs parallel to the Andes Mountains range and varies in width from 5 to 30 km approximately. Topographically, it comprises levels ranging from 0 to 2,700 meters above sea level (m.a.s.l), as shown in Figure

37. Five staggered geomorphological features also establish the city: coastline, coastal plains, hills, valleys, ravines, and mountains.

The coastline (a) extends from northeast to southeast parallel to the maritime edge and is dry land width of 1 to 2 km. In this area are also formed by wind action, the beaches. The coastal plains (b) are areas of moderate slope (10° to 20° inclination) located parallel to the coastline between the coastal edge and the foothills of the Andes Mountains. The most extensive flats are located in the lower areas of the three valleys that cross Lima (Lurin, Rimac, and Chillon) and are covered by clay, sand with gravel, and silt. In the dejection cones, they cover an area between 25 to 40 km along the rivers. In addition, they cover an area of 100 km^2 where 70% is cultivated land.

The third geomorphological unit that stands out in the metropolitan area of Lima is the hills (c). These areas surrounded the beginnings of the Cordillera Occidental Mountain range and were generated by erosion caused by the rivers that flow through the city. In many cases, they are made up of rocks (limestone), and in others, they are covered with sand. Among the most important are Cerro Cachito, Señal Cavero and the elevations of Cerro Atocongo. The valleys and ravines (d) were born in the continental separation and were great drainage channels of the basins in the past and today are the result of the erosion process. These areas are called the lower zone of the slopes (higher and of mountainous composition), and they are steep and abrupt in the form of a canyon. In the middle zone, terraces develop at different sublevels that are occupied by informal settlements today in many cases. The steeper areas of the ravines are in constant danger from landslides and mudslides. The development of informal settlements due to anthropogenic agents (human activity) has increased their instability. Finally, there is the mountainous slope (e) with an abrupt topography that contains the ridges of the Andean Mountain range, as it represents the transition area between the western mountain range and the coastal plain. The highest peaks are between 900 and 2700 meters above sea level (MML, 2014, pp. 125-127).

It should be noted that a series of more specific sub-traits can be analyzed within each of the five general geomorphological features. However, for the research, it is not necessary to go into more detail.

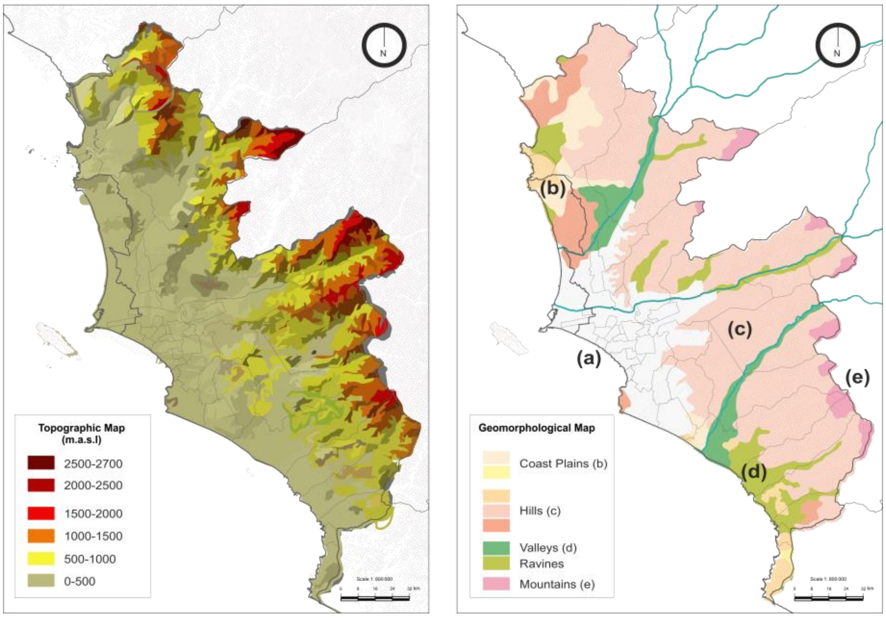


Figure 37: Geomorphological distribution and topography in ML

Source: Created by author, adapted from MML, 2014.

4.3.2 Geological Base

As established in 1996 by the National Institute of Natural Resources (INRENA), Lima's soil is divided into three large groups and spatially related to the geomorphological features previously analyzed. This classification was made based on the typologies established by the FAO (OA CHIRILU and GIZ, 2019). In summary, the geological base of the city is composed of the flat areas by soils developed by alluvial cones (Fluvisol éutrico) and by gravelly soils (Regosol éutrico) in the central regions of the city, as shown in Figure 38. There are also eolian plains in districts such as Ventanilla or Villa El Salvador formed by sands characterized by excessive drainage and arid conditions that support xerophytic vegetation. Highly saline soils of marine origin represent a smaller area. Slope areas between 25% and 75% are composed of volcanic rock, sediments, and intrusive mountains (Aguilar and Alva, 2013; MML, 2014).

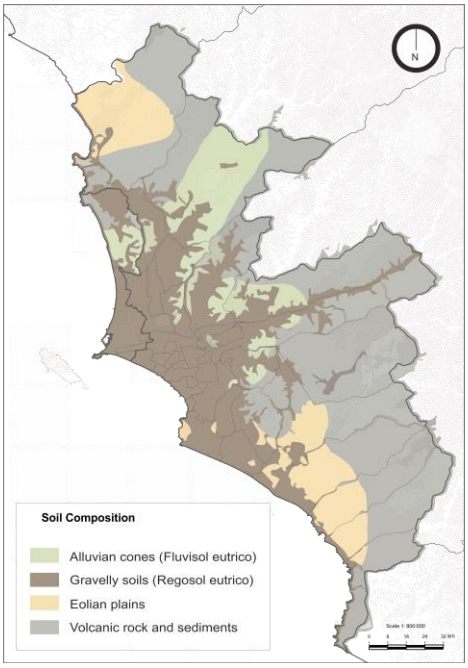


Figure 38: Geological base in ML

Source: Created by author, adapted from Aguilar and Alva, 2013; MML, 2014

4.3.3 Climate

According to the Köppen-Geiger climate classification, the city of Lima, like Cairo, Las Vegas, or Antofagasta, has a warm, arid climate (BWh) in a large area of the territory. However, due to its location on the coast and its geographic characteristics, it also has tropical features that allow it to have a temperate climate, which Köpper calls a semi-tropical arid climate (BWhn) (Peel, Finlayson and McMahon, 2007). That is, on the one hand, there is the presence of cold coastal winds (Humboldt Current) that cool the air and prevent the formation of clouds, and on the other hand, the existence of a physical barrier (Andes Mountain range) that blocks the clouds coming from the Amazon region. Thus, Lima has an average annual temperature of 18°C, with no regular rainfall but humidity percentages that exceed 98%, which translates into a continuous layer of fog. Nevertheless, these conditions are not constant throughout the city, as the different altitudinal levels play an essential role in generating microclimates. Thus, during the winter season (between May and November), the temperature can range from 8°C to 18°C, where the highest values are observed on the coast due to the thermoregulatory effect of the sea. Therefore, the temperature decreases as the distance from the ocean increases. On the other hand, during the summer (December to April), the temperature ranges between 18 and 25°C, with the highest values observed on the coast and decreasing progressively as the area is at a higher altitude (MML, 2021).

However, these regular characteristics can be affected, as has happened throughout history, by seasonal climatic phenomena such as El Niño or La Niña. El Niño is the increase of the Sea Surface Temperature (SST) in the central equatorial Pacific coast and the change of atmospheric pressure in this area. It is recognized as the primary modulator of interannual climate variability and the water cycle. During an El Niño episode, which fluctuates between every 3 to 8 years, in the case of Lima, air temperature increases, wind speed, and ocean currents decrease, and finally, precipitation increases. Although this fact in a semi-arid zone like Lima has positive impacts such as the recharge of the city's aquifers and wetlands and the regeneration of dry forests, it represents above all adverse effects that have historically affected the living conditions of the population. In the higher areas of the territory, increased rainfall erodes the soil causing landslides, endangering the lives of thousands of inhabitants who live on the slopes and riverbanks. In low-lying areas, flooding occurs and loss of the agricultural regions and crops (SENAMHI, 2014). During 2017, the last El Niño phenomenon of extraordinary intensity (the highest until today) was recorded on the Peruvian coast and severely impacted the capital city. According to INDECI estimates, it left 18 thousand people affected in Lima, 17 deaths, 124 bridges destroyed, 962 km of roads destroyed, more than 3 thousand houses destroyed, 263 educational institutions, and 75 health establishments 10 ha of cultivated areas affected. Additionally, this last El Niño event highlighted the vulnerability of the city's water and hydroelectric infrastructure, leaving the population without drinking water service for several days and, in some cases, without electricity in the streams near the stations (INDECI, 2017).

The La Niña phenomenon is a climatic event that is part of the natural cycle of El Niño. The latter is a warm phase, while La Nina is the cold phase and presents conditions contrary to the former. La Niña is characterized by cold and long-lasting temperatures and a reduction in precipitation, which eventually risks the population. From the social aspect, the decrease in air temperature with anomalies below normal conditions, accompanied by other climatic factors, such as increased humidity and wind speed, increases the feeling of cold in the coastal population. There is even an increase in respiratory infections, affecting the vulnerable population in informal settlements as well as children (0-5 years) and the elderly. From the economic aspect, the change of temperatures in the coastal zone also influences the loss of harvest areas (rice, corn, potato) and the removal of marine species such as the anchoveta from the maritime edge, forcing anglers to enter deeper waters for fishing. From the hydric aspect, the reduction of precipitation can cause a decrease in available water resources (CENEPRED, 2013).

4.4 Ecological Infrastructure (EI)

Lima has a dynamic landscape characterized by very distinctive natural and anthropogenic elements adapted to the environmental conditions that shape the city's urban form and have greatly influenced the dynamics of the population's habitability throughout history. According to INRENA in 1995, the city has three Life Zones: Subtropical Desiccated Desert (dd-S), Subtropical Superarid Desert (ds-S), and Subtropical Low Montane Perarid Desert (MML, 2014, p.131). As shown in Table 5, Lima's Life Zones give form to the different environmental units differentiated by temperature, altitude, climate, and type of endemic vegetation. Therefore, the most important ones are coastal marine littoral, coastal wetlands, rivers, agricultural valleys, coastal hills, arid pampas, arid Andean mountains, and urban green areas (Eisenberg *et al*., 2013, pp. 24-26).

N°	**Denomination**	**Altitude**	**Annual Biotemperature**	**Ratio Annual Potencial Evaporation**	**Annual Precipitation**	**Humidity**	**Vegetation**
1	Subtropical Desiccated Desert (dd-S)	1-500	18 ° - 23 °	32/64	2.2-22.9 mm	Dried	Scarce presence of halophyte plants
2	Subtropical Superarid Desert (ds-S),	500-1,000	19 ° - 21 °	16/32	30-50 mm	Superarid	Gramineae and in wet areas Shrubs
3	Subtropical Perarid Desert (dp-MBS)	2,000-2,500	13 ° - 17 °	8/16	60-105 mm	Periarid	Xerophyte shrubs and seasonal herbs

Table 5: Lima's Life Zones

Source: Created by author, adapted from MML, 2014; Eisenberg *et al*., 2013.

Nevertheless, according to what was analyzed in Chapter 2 (Theoretical Framework), the Ecological Infrastructure (EI) is recognized as blue and green infrastructure (BGI) of natural and anthropogenic character (including Gray Infrastructure) whose purpose is to provide ecosystem services related to the urban water cycle. Therefore the research delimits a deeper analysis only to natural green (hills and wetlands) and artificial (parks and valleys), gray (public spaces and others) and blue elements also natural (rivers, wetlands) and artificial (irrigation canals), as shown in Figure 39 (Ghofrani, Sposito and Faggian, 2016).

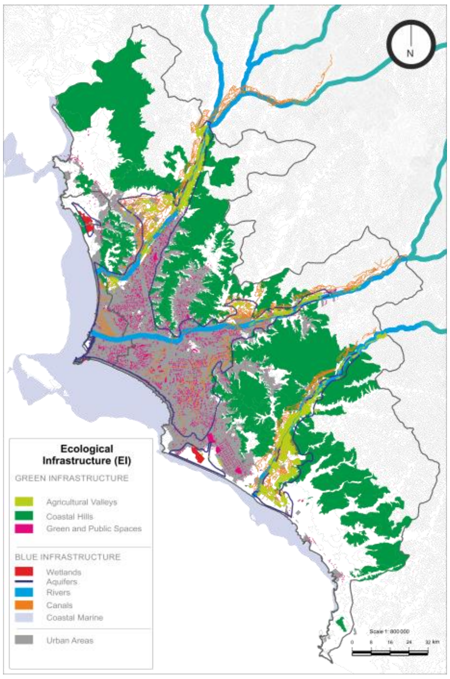


Figure 39: Ecological Infrastructure in ML

Source: Created by author, adapted from MML, 2014

- Natural Green Infrastructure: Coastal Hills and Wetlands

Metropolitan Lima has a vegetation cover of 40,529 hectares, equivalent to 14.4% of the city's territory, differentiated between natural and anthropic vegetation. Figure 40 shows that the natural vegetation cover is made up of coastal wetlands and coastal hills. The last ones are seasonal ecosystems present during the winter season. They are a unique type of natural vegetation present mainly in Peru and Chile and represent 53% of the city's vegetation cover in 13 districts of the capital. The coastal hills of Lima develop after an annual greening process thanks to the condensation of humidity and thermal inversion creating fog between July and November on the western slopes of the hills of the Andean Mountain range (MML, 2014, pp. 138-142).

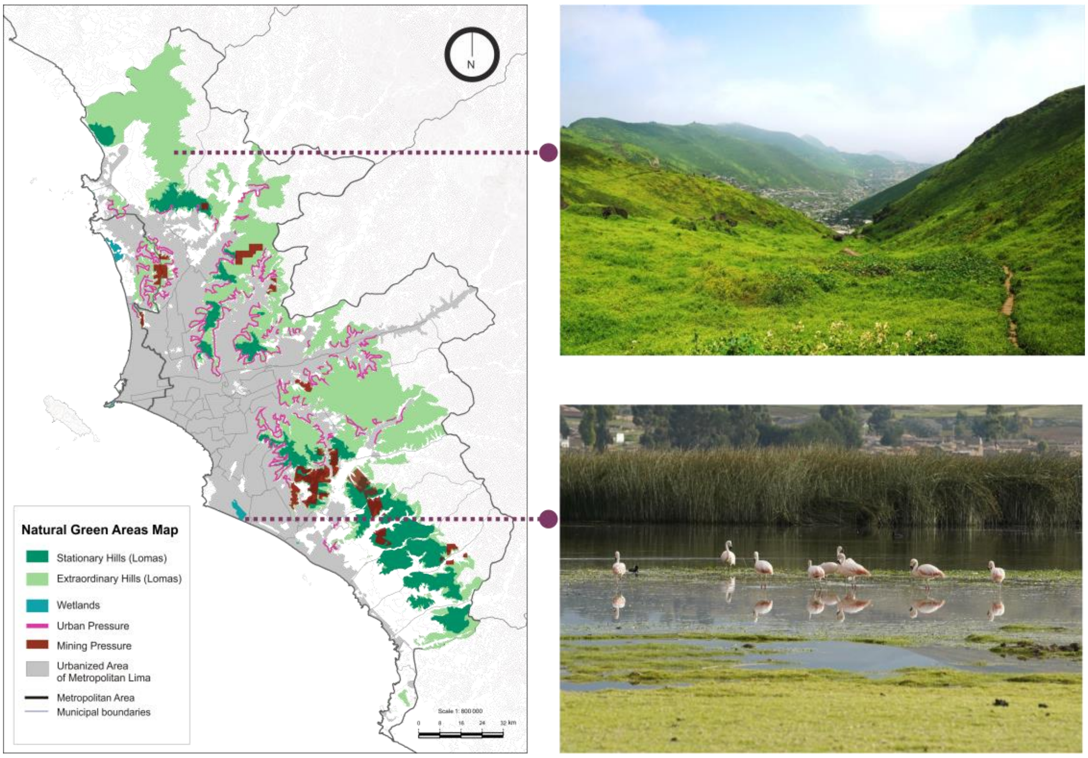


Figure 40: Natural Green Infrastructure in ML

Source: Created by author, adapted from MML, 2014; ANDINA, 2019; 2020.

Today the hills form a green belt that surrounds the city of Lima from Pasamayo to Pucusana, cut by the Chillon, Rimac, and Lurin valleys and the dry creeks. The hills cover an area of 21, 279 ha, equivalent to approximately 7.6% of the city's territory, a surface that can triple in size in the event of climatic phenomena such as El Niño (previously analyzed).

The importance of the hills is centered on two aspects; first, its landscape component significantly improves the aridity that characterizes Lima, as shown in Figure 40. Second is its ecological contribution by being the natural habitat of more than 21 endemic species. The most well-known are the Amancaes flower (*Ismene amancaes*), shrubs, xerophytes, herbaceous and gramineous plants, and wildlife adapted to the climatic conditions, soil, and topography (slope) of the hills, acquiring the ability to survive prolonged periods of drought.

The largest continuous area is located in the south (Lomas de Lucumo) in the district of Pachacamac. However, like many of Lima's natural and atrophic regions, the hills are under pressure mainly due to the urban expansion process, drastically reducing their limits and dimensions annually. Indeed, more than 59% of them (12,569 ha) are declared by MINAGRI as fragile hills, mainly due to informal occupations, land trafficking, and illegal mining activities. Although the Metropolitan Municipality of Lima (MML) has been developing various programs and even regulations for their conservation and promotion as ecotourism areas, the reality is that much more articulated, and robust efforts are required (MML, 2014, pp. 138-142).

Another component of the city's natural green infrastructure is the coastal wetlands. Although these are considered blue bodies and will be analyzed later, they are also made up of an essential green component that covers an area of 180 ha corresponding to vegetation that does not cover the water bodies or zones within the scope of influence of the wetlands. This vegetation, predominantly emergent and submerged aquatic species, presents particular adaptations to live in an environment flooded with water and feed on the subsoil rich in salts and organic matter. Species such as salt grass, sesuvium, and cattails (*Typha domingensis*) have a significant presence in wetlands (MML, 2014, pp. 134-135). More information can be found in the Blue Infrastructure section.

- <u>Anthropogenic Green Areas: Parks and Agricultural Valleys</u>

The World Health Organization (WHO) in 2009 indicated that the ratio of square meters of green space per inhabitant should be considered one of the indicators of health in sustainable cities, citing nine square meters (m^2) of green open space per inhabitant as the recommended standard (WHO, 2010). Although several contradictory sources establish even higher recommendations (up to 16 m^2), the truth is that most cities struggle to reach this recommended minimum while others intend to exceed it substantially. In the Peruvian context, the city of Lima is far from achieving this recommendation. According to Peruvian regulations, green areas of anthropic origin are described as *'all those public or private spaces destined for greenery within the urban area.'* Although they cover an area of 7,970 ha, equivalent to almost 20% of the city's vegetation cover, the truth is that more than half (57% of the total) are private green areas without free access for the population and therefore not included in the analysis.

For the research, public green areas (43% of the total) are categorized in general typologies that allow for greater standardization: local parks, metropolitan parks, green areas in central medians, zonal parks, and zoos, among other small-scale parks grouped as Others. In fact, and as stated above, the latest inventories show that the public green space for Metropolitan Lima reaches 3,457 ha (Lima Province with 92.8% and Callao with the remaining 7.2%), i.e., the equivalent index is 3.06 m^2 / inhabitant, considering a population of 10.5 million inhabitants, a figure well below the WHO recommendations (MML, 2014, p.144). It is also one of the lowest in the Latin American region, only below Bogota, which has 4.1 m^2 / inhabitant and is far from the 12.6 m^2 / inhabitant of Santiago de Chile, as shown in Figure 41. This equation would merit further analysis since not all measure green areas in the urban context in the same way, but it is beyond the specific objectives of the research (MML, 2014, p. 595).

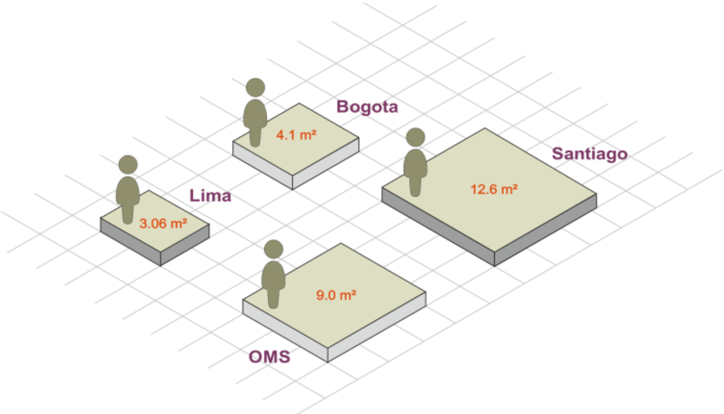


Figure 41: Green open space per inhabitant in ML

Source: Created by author, adapted from MML, 2014; WHO, 2010.

Seen spatially, the distribution of green areas in Lima is highly heterogeneous and, in many cases, is not related to other important variables such as housing density or levels of precariousness in the city. For example, the central area of Lima contains 35% of the city's public green spaces. However, it only represents 4% of the total territory. At the same time, the districts with higher poverty rates and higher housing density have less accessibility to these areas, which further accentuates their relationship with social segregation, as shown in Figure 42 (MML, 2014, pp. 589-595). This aspect is due to the formal land occupation process that characterizes Central Lima, as opposed to the informal occupation that represents the peripheral zones where the development of informal settlements monopolizes almost all the land. The lack of planning in their maintenance and administration must be added to the high lack of green areas (6,065 hectares of deficit).

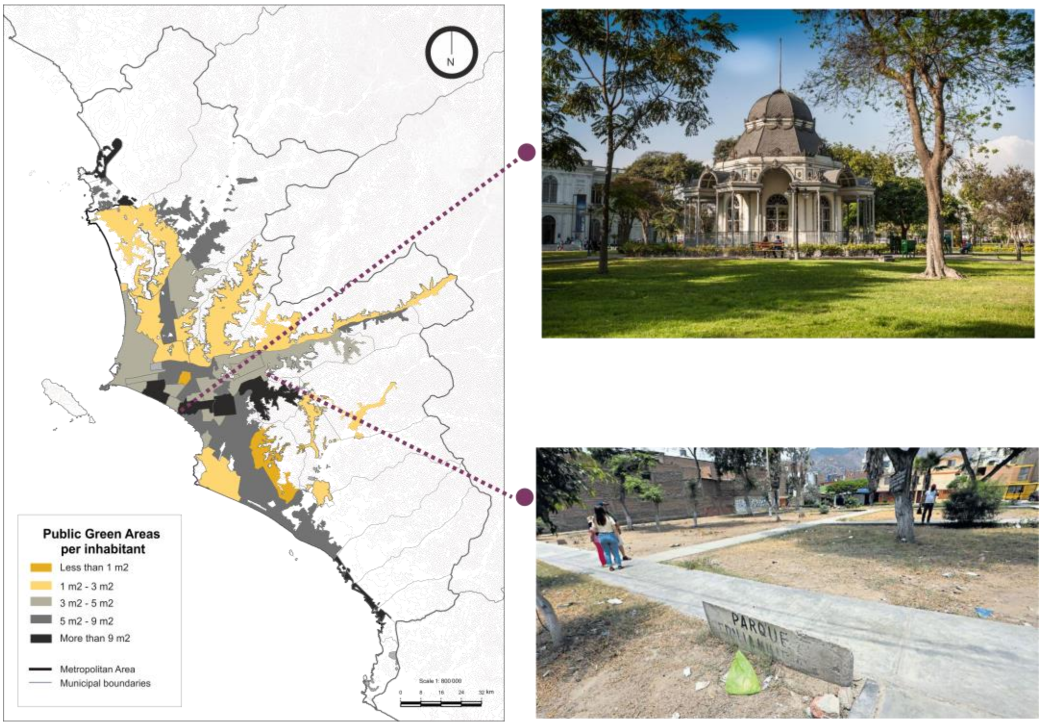


Figure 42: Distribution of public green areas per inhabitant in ML

Source: Created by author, adapted from MML, 2014; EC-El Comercio, 2018a; 2019

Peru's National Building Regulations establish that the minimum green area required to be classified as a park is 800 m² (MVCS, 2006, p.26). A significant percentage of the Metropolitan Parks are within this minimum area range; however, many parks at the local (district) level do not reach the required minimum surface area. It is worth mentioning that according to the World Health Organization (WHO), green space in cities refers to *"urban space covered by vegetation of any kind,"* implying that other available green areas such as tree canopies could be included in the calculation. However, no consistent information or an updated inventory at the metropolitan scale has been found that would allow incorporating this information in the research (WHO, 2016, p.7). An important aspect that deserves special attention is the irrigation system of Lima's green spaces. A high percentage of the municipalities in charge of this service use potable water and flooding techniques that are neither efficient nor sustainable. A more detailed analysis can be found in the UWMB section of this chapter.

The valleys are another component of green areas of anthropic origin and are part of the green cover of Lima. Due to their fertile soils, the valleys have been used for agriculture as a source of subsistence and later as an economic activity since pre-Hispanic times. From the hydraulic aspect, they are essential for the recharge of the aquifer that supplies the city. At present, it is estimated that the agricultural area occupied by the Chillon, Rimac, and Lurin valleys covers 11,100 hectares, equivalent to less than 4% of the city's total territory, as shown in Figure 43. Urban expansion and the city's real estate market put pressure on the conservation of Lima's agricultural valleys. Indeed, in the last decades, 90% of the original area of the Rimac River valley has been lost, 68% in the Chillon and 17% in Lurin. The latter has been recognized as the last great agricultural valley of the city, even though this image is weakening daily. Therefore, it is necessary to develop strategies for its conservation and sustainability, generating added value to the production of tubers (potato and sweet potato) and other crops (MML, 2014, p.136).

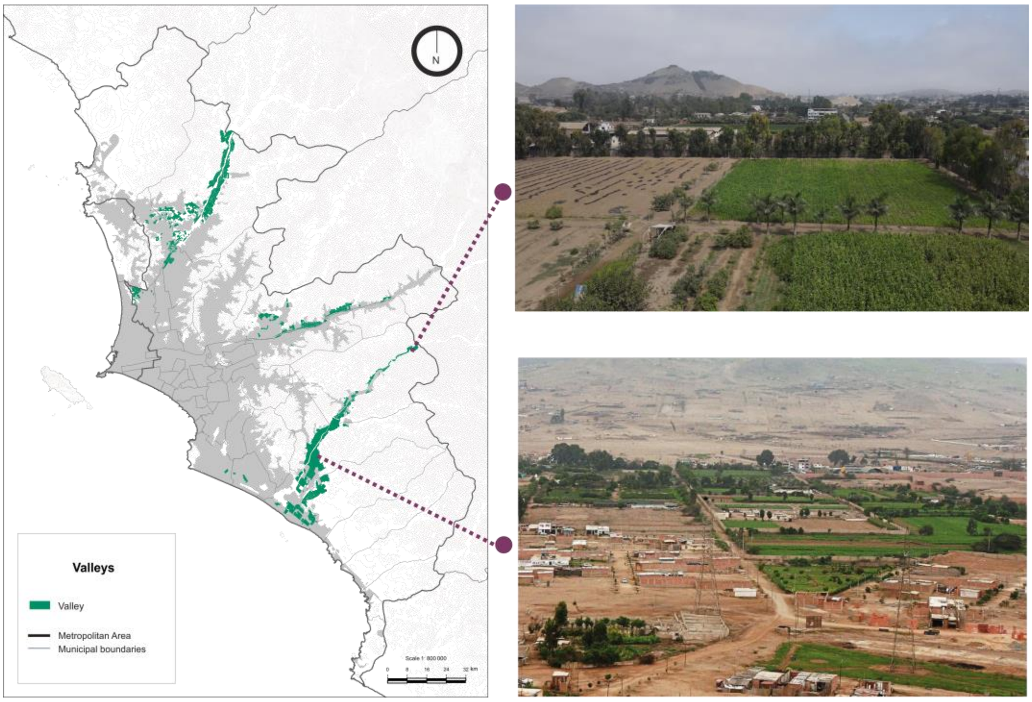


Figure 43: Valleys in ML

Source: Created by author, adapted from MML, 2014; Miñan, 2020; Escobar, 2021.

- Gray Infrastructure: Public Spaces

According to the WHO, one of the leading indicators of the relationship between sustainable spaces and good health is access to urban infrastructure for social, recreational, and survival development, hence the importance of being at close distance and in adequate proportion to meet these needs of the population (OECD, 2012). In this sense, other elements that are part of the Green Infrastructure are the gray elements, i.e., all those anthropogenic public spaces (created by man) formed by hard surfaces.

According to Peruvian regulations, anthropogenic public spaces are zoned spaces such as parks, squares, and plazas, mainly for sports. However, the law also incorporates others that fulfill a public role without land zoning, such as streets, avenues, among many others. The essential function, defined in the Metropolitan Ordinance No. 525 (2005), is to be urban life centers and concentrate multiple civic, recreational, social, cultural, and economic activities. In total, there are 478 zoned public spaces distributed heterogeneously throughout the city and covering 90.05 ha, or less than 1% of Lima's total area. For the research, zoned public spaces have been categorized into main squares (or "plazas de Armas"), district squares, small squares, and multifunctional platforms or neighborhood spaces. The main squares are closely related to the colonial period of the city, a typology that has permeated the urban fabric of Lima, and today, as in the past, they are defined by their civic vocation. Their boundaries are home to the district's main public buildings.

On the other hand, the district squares are generally smaller in scale than the main ones, and their function is more of a social and economic nature. The small squares also have a colonial style and are located mainly in the historic center, specifically on the corner of the blocks. The multifunctional platforms are spaces located in areas in the consolidation process, appearing informally in the plot to meet the sporting and social needs of the population (MML, 2014, pp. 581-582).

Public spaces play a vital role in the social development of citizens. They are places for meeting, gathering, exchange, or just being; as Jan Gehl explains, *"Being with others, seeing and hearing others, receiving impulses from others, imply positive experiences, alternatives to being alone. One is not necessarily with a specific person, but one is, nevertheless, with others "* (Gehl, 2011, p.17). Given the importance of public spaces, as provided in the Peruvian regulations and recommended by the WHO, their accessibility should be universal. Nevertheless, this statement does not translate into reality. When analyzing the accessibility of zoned public spaces in the city and considering distances of no more than 300 meters, it is found that in Metropolitan Lima, about 23% of the population access these spaces within walking distance. In contrast, the other 77% do not do so because they cannot find one nearby.

As previously mentioned, the distribution is not heterogeneous, and at the district level, there are severe differences, as shown in Figure 44. Of the 43 districts that make up the city, three communities have a higher proportion of coverage (distribution) based on their urban area: San Juan de Miraflores, Ventanilla, and Villa Maria del Triunfo. In contrast, districts such as Puente Piedra, San Juan de Lurigancho, Callao, Punta Hermosa, Punta Negra, and San Bartolo, have a non-homogeneous coverage of public spaces. When extrapolating the information with housing density, the figures are also revealing: the ratio of sqm per inhabitant is meager throughout the city, which implies that 83% of the population near public spaces receives less than 1m² per inhabitant. The analysis also shows that only a small group of city dwellers in districts like Cercado de Lima or San Isidro have a 9 m²/inhabitant (MML, 2014, p. 583).

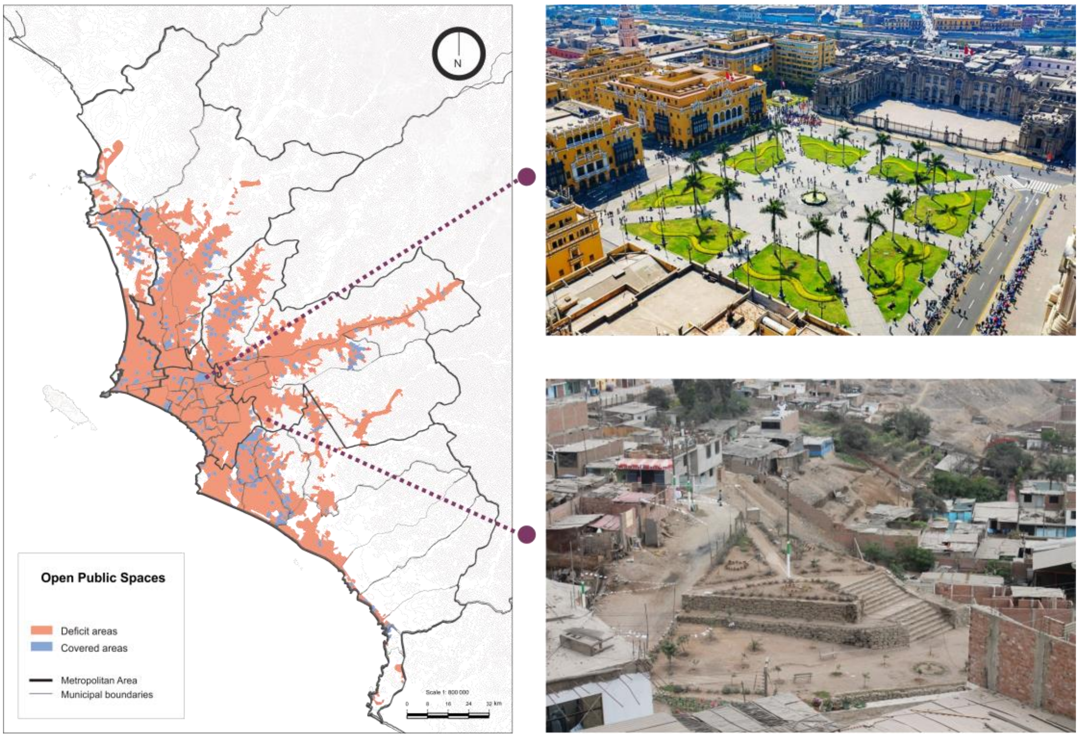


Figure 44: Distribution of Open Public Spaces in ML

Source: Created by author, adapted from MML, 2014; Franco, 2015; Vásquez, 2021.

Streets are another typology of public spaces and are found without zoning regulations. Although the understanding of the urban fabric in Lima merits an in-depth analysis in itself, it is necessary to mention general information that could be of vital importance when analyzing the potential of public spaces in the city for the development of an integral water-sensitive vision. In Lima, approximately 8.5% of the territory (23,839 Ha) is occupied by the city's road system, composed of roads of different scales and relevance (MML, 2014, pp. 570-574).

In Lima, there is another important group of spaces that, although residual spaces of the city, have a high potential for public spaces and could be integrated into the system after appropriate treatment. Among them are the buffer areas of pre-Hispanic archaeological heritage, zones of environmental liabilities (quarries and dumps), areas of electrical services, solid waste infrastructure (landfills), and protection areas (marginal belts) (MML, 2014, p.605).

In the case of pre-Hispanic or even colonial archaeological heritage buffer areas, near the Rimac corridor, there are 36 properties with potential polygon (937.6 Ha); near the Chillon corridor, there are 3 with a surface area of 19 hectares. In comparison, near the Lurin corridor, there are 21 properties (407 Ha), all of which could be incorporated into the system. On the other hand, one of the main problems that will be analyzed later in the research is the presence of areas of environmental liabilities and landfills in the river fringes of Lima. In the 2013 inventory conducted by the Municipality of Lima, 193 ha were found to be occupied by dumps and 2,628 ha where 21 quarries were operating, most of them close to the edges of the Chillon

River to its soil characteristics. In the Lurin area, there is an area of approximately 19.4 ha used as a sanitary landfill that has reached its useful life and needs to be closed. In the city, the marginal areas on the borders of the three rivers that cross the city have been informally occupied by informal settlements or are informal dumping grounds for municipal and construction solid waste, severely affecting the water quality of the blue bodies. The approximate area is 2,636 Ha, of which informal settlements occupy 13% and 87% are free but polluted. There are also some electrical installations in the city (high-tension towers) to provide service to different users in the urban area. In Lima, approximately 98.7 ha have been identified that cover the electrical service, concentrated in Lima Cercado. These flat areas and the other residual areas of the city mentioned previously have, after a correct treatment, the potential to be incorporated into the system (MML, 2014, pp. 605-6015).

- Blue Infrastructure in Lima: Rivers, Wetlands, and Irrigation Canals

Another component of the EI is the blue infrastructure. It is very diverse, not only because of its morphological characteristics (surface or groundwater) but also because it is composed of natural elements like the Rimac, Chillon, and Lurin rivers and artificial components (canals) whose historical value is undeniable.

From the natural aspect, the rivers Chillon, Rimac and Lurin feed the fluvial courses of the city, as shown in Figure 45. One of the most relevant characteristics of the three surface water sources is their irregular hydrological regime, with two very marked periods: the low water season (June to November) and the flood season (December to May). The source of the Chillon River is located on the western flank of the Cordillera Viuda and flows into the Pacific Ocean with an average annual flow of 8.97 m³/s (OA CHIRILU and GIZ, 2019). Its flow variation is the most significant since 63% of the annual volume is discharged between January and March, 20% between April and May, 10% between June and October, and 7% in November and December. During its rainfall periods, it causes maximum discharges, causing major landslide and flooding problems along its course. The Chillon River basin covers 2,353.53 km², of which 46.5% is outside the city boundaries (MML, 2014, p.148). The presence of active dumps of construction and demolition waste in the river's marginal strip increases flooding hazards due to the strangulation of the river's natural course (MML, 2014, p.138).

In the case of the Rimac River, it originates in the Nevado Pacay 132 km northeast of Lima and eventually flows into the Pacific Ocean and is the primary water source that supplies the city (OA CHIRILU and GIZ, 2019). The Rimac River is part of the Rimac basin, which exceeds the limits of ML and flows through different altitudinal levels along its course with an average slope of 3.3%. Its basin covers a total surface area of 3,132 km²; however, only an extension of 467.2 km² and a river course length of 56.9 km is within the city. Also, the rainfall levels are low and diametrically different from those of the upper basin. The river's average flow is only 28.6 m³/s, which supplies 80% of Metropolitan Lima's water needs. Exceptionally, a maximum flow of 385 m³/s was reported during the 1940s, but this has not been repeated since then (MML, 2014, p.147). Although water quality will be analyzed in detail later, it is essential to mention that the Rimac River is one of the most polluted rivers in the country. This situation is mainly due to uncontrolled dumping of domestic waste and a high degree of neglect of river maintenance in the lower zone, and mining waste in the middle basin (MML, 2014, pp.136-137).

The Lurin River originates in the Surococha snow-capped mountain and runs 111.2 km with a 4.7% gradient until it flows into the Pacific Ocean. Its average annual flow is much lower than that of the Rimac River at only 4.43 m^3/s, but its importance is more agricultural than residential for Lima (OA CHIRILU and GIZ, 2019). Compared to the Rimac River, the Lurin River has better water quality. However, in the Pachamac area, there are high volumes of domestic garbage and untreated wastewater from the San Bartolo Wastewater Treatment Plant (WWTP). This situation is worrisome, considering that the Lurin Valley is the most important agricultural area in Lima, and its lands are irrigated with water from the river (MML, 2014, p.138).

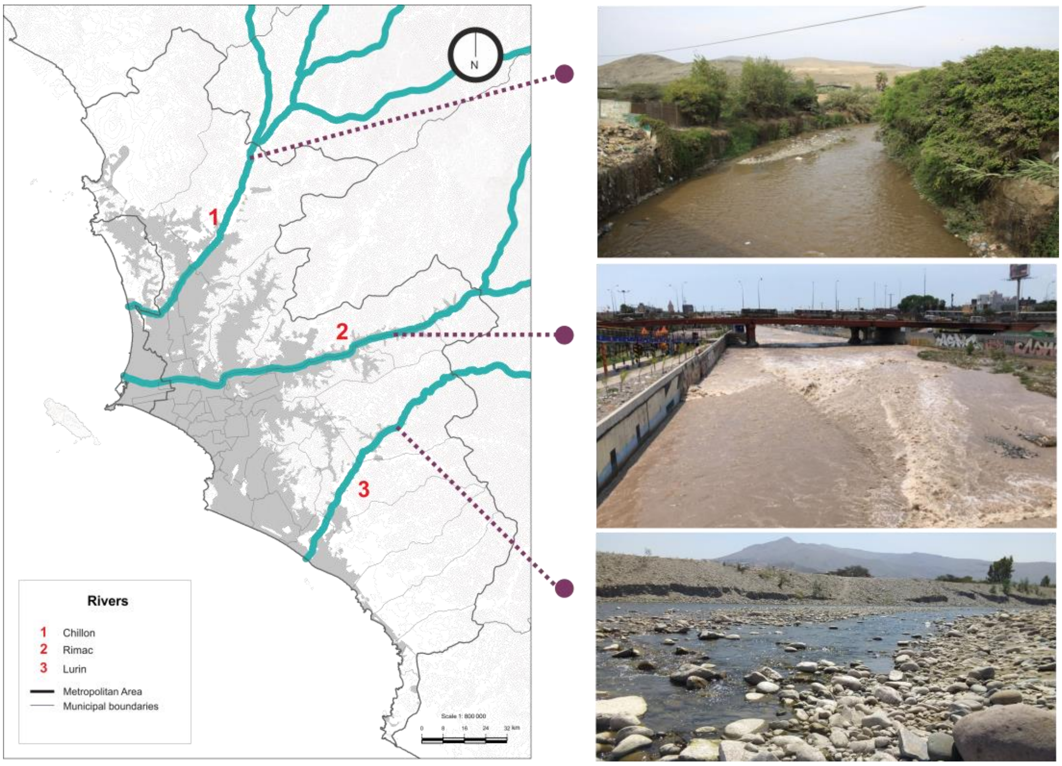


Figure 45: Chillon, Rimac, and Lurin Rivers in ML

Source: Created by author, adapted from MML, 2014; MACROGESTION, 2019; SERVINDI, 2020; ANDINA, 2021a

Understanding the city's relationship with the rivers is somewhat complex and includes other aspects that have not been considered as part of the research. However, it is possible to assure that this relationship is highly algid. It could be presumed that the close city-river relationship between Lima and its three rivers is essentially the result of the lack of an orderly growth of the city and the absence of an urban planning instrument that incorporates them for their hydraulic and landscape qualities. At present, illegal occupations cause narrowing of its course, pollution, and significantly reduced water quality. The lack of awareness on the part of the population reinforces this image of urban fabric fractionators (Rocha - Felices, 2011).

The groundwater that runs through ML, also called aquifers, is an essential source of water supply for the city, both for consumption by the population and productive activities. Aquifers are fed by filtering through riverbeds, canals, and areas under irrigation, but above all by subterranean flow from the upper parts of the basin. In Lima, there are two, the Rimac-Chillon aquifer with an extension of 390 km^2 and a depth that varies between 100 meters and 400 meters, the latter value identified in districts such as La Perla. The Lurin aquifer is the second aquifer that supplies the city and is much less extensive and thicker, varying between 1 to 20 meters deep in districts such as Cieneguilla, as shown in Figure 46. Although Lima's aquifers are the largest source and reserve of freshwater, they are under pressure like other elements of the city's blue infrastructure. To a large extent, their recharge is diminishing due to the progressive disappearance of agricultural valleys and the sealing of the soil surface due to urbanization (MML, 2014, p.138).

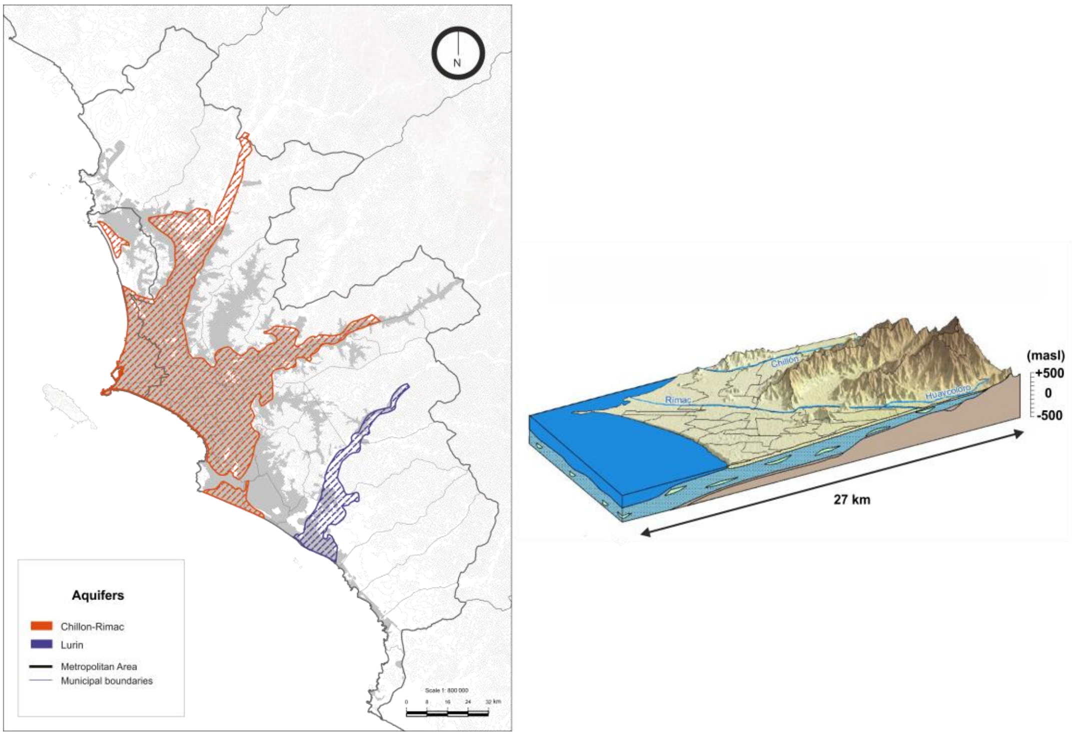


Figure 46: Chillon-Rimac, and Lurin aquifers

Source: Created by author, adapted from MML, 2014; ANA and GIZ, 2018.

Another natural element that makes up Lima's weakened blue infrastructure is the so-called wetlands, essentially maritime marshes with fresh groundwater flows and marine intrusions. These also have a vegetation cover component previously analyzed. Their importance in the system is centered on water regulation in the river basins and the purification by naturally filtering pollutants. They also represent an essential biodiversity focus by harboring a high potential for terrestrial and aquatic flora and native and migratory fauna species (birds, fish, amphibians). Their importance also transcends the socioeconomic aspect by being a collection point for reed, an essential element in handicraft products. Throughout ML, they cover 593.7 hectares, equivalent to 0.21% of the city's territory.

The most significant proportion of wetlands is concentrated in the province of Callao (53%) through the wetlands of Ventanilla and Arenillas. In comparison, the other 47% is focused on the region of Lima through the marshes of Villa, wetlands of Santa Rosa, and Pachacamac, as shown in Figure 47. Although most of the wetlands are protected by being recognized as Regional Conservation Areas by SERNARP, the fact is that over the last few decades, a significant percentage of the areas of influence have been lost, and today they face pressures such as increasing pollution by the population. Only two of the wetlands, the Pantanos de Villa in the district of Chorrillos and the Arenilla wetlands in La Punta, are connected to the urban fabric and landscape as public spaces after the creation of eco-tourist circuits and even the incorporation of interpretation centers for educational uses. In the other three cases, wetlands of Ventanilla, Santa Rosa, and Pachamac, their articulation is still a great challenge (MML, 2014, pp.135-136).

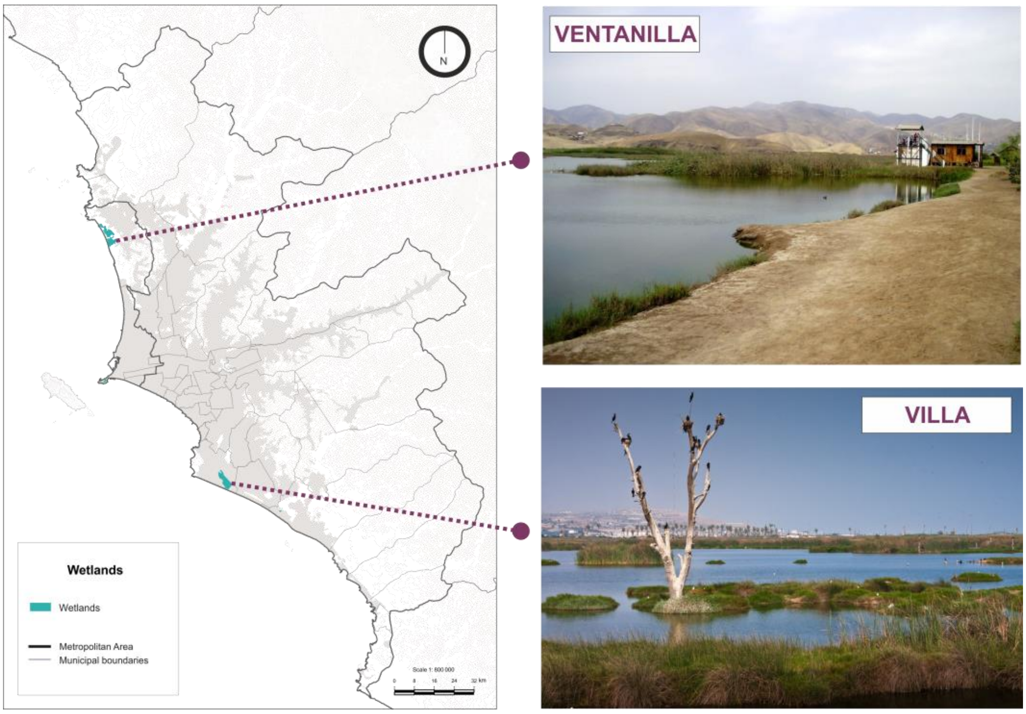


Figure 47: Natural Wetlands in ML

Source: Created by author, adapted from MML, 2014; Mapio, 2020

From the artificial sphere, the network of pre-Hispanic irrigation canals is also another element of the city's blue infrastructure, and, as previously mentioned, they still exist. Although a large percentage of the original network was lost due to population growth and urban pressures over time, the reality is that it is not given the importance it deserves. This aspect is mainly due to a lack of knowledge of its real water, social, and landscape potential. There are currently 18 diversion canals (primary) attached to small secondary canals that cross the city, allowing the irrigation of green and agricultural areas in 23 districts of Lima, as shown in Figure 48. The network is connected to the three main rivers; in the case of the Chillon river, seven canals (17 km), five canals of the Lurin river (36.6 km), and six canals of the Rimac river cross 87 km of the city, the most important being the Surco canal followed by the Huatica canal. Historically, the spatial concept and its relationship with the city have lost their strength by burying a large part of the canals. Indeed, today only 8 km of the Surco canal (30 km) are exposed, and 22 km are sealed, running through the central areas of the city's main avenues. The relationship between the canals and the population is also fragile, especially in peripheral regions such as those near the Lurin River, where the canals are a kind of exposed sewage system that significantly affects not only the quality of life of the inhabitants but also the quality of the water that then reaches the ocean.

According to estimates, a total of 64 km of the network has a high potential for rehabilitation and transformation to benefit the population and the urban landscape (MML, 2014, p.616). It is essential to develop actions that incorporate and improve the city's blue infrastructure network due to its importance in maintaining its ecosystemic balance and its high potential to establish water-sensitive strategies.

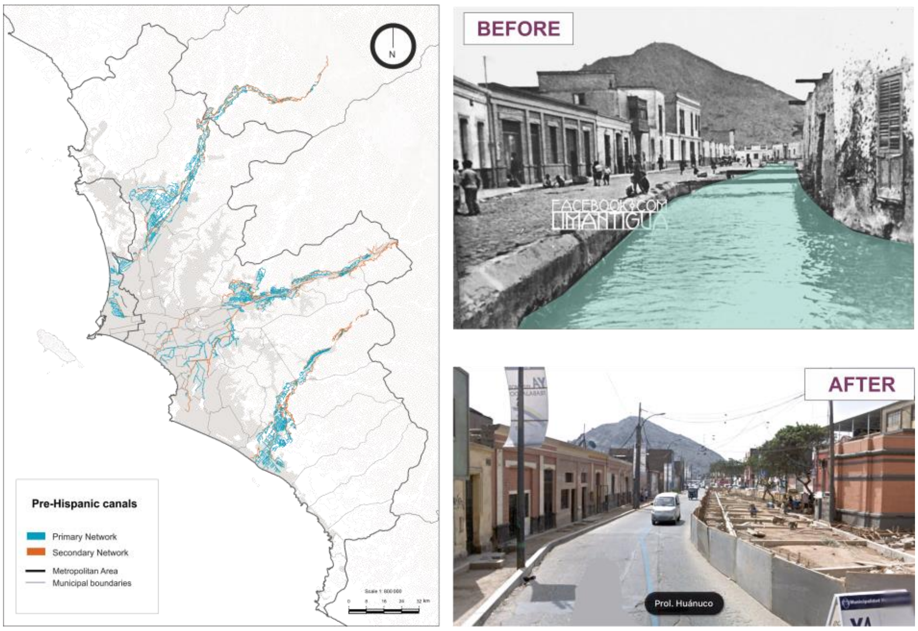


Figure 48: Pre-Hispanic canals network in ML

Source: Created by author, adapted from MML, 2014; LIMA ANTIGUA, 2020.

4.4 Water Governance

Institutional water reform is one of the critical aspects when seeking to create water-sensitive communities. The country has consolidated a legal and institutional framework for water resources management at the national level during the last decades. However, several governance gaps still delay its proper implementation and become even less effective at the local level (OECD, 2021a, p.14). In this sense, it is necessary to briefly review the water governance systems in the Metropolitan area of Lima. However, as previously mentioned, the city of Lima from the water aspect is part of the Chillon-Rimac-Lurin (CHIRILU) basin. Therefore, it is necessary to analyze the existing principal regulations, the actors, and their relationships with each other from a basin perspective, and the main characteristics of the hydrological and territorial administrative boundaries. The development of this section is an attempt to understand the institutional competence and answer the research question *What is Lima's Governance capacity to address water challenges?*

4.4.1 Regulatory and Institutional Framework

Peru currently has a solid regulatory system resulting from a long process of recognizing shortcomings and gaps that in many cases left room for ambiguity and overexploitation of water resources without proper State action. Historically, this process of change began with the General Water Law (Law No. 17752) enacted in 1969, which in its Article 1 declares that water, without exception, is the property of the State and that there is no private ownership of water or acquired rights over it. The Law also establishes that the justified and rational use of water can only be granted in harmony with the country's social interest and development.

Article 128, which is still in force, consolidates the responsibility of water administration to the Ministry of Agrarian Development and Irrigation (MINAGRI), excluding water-related to mining or medicinal activities, which are the responsibility of the Ministry of Health (MINSA). Subsequently, in Articles 66 and 67 of the 1993 Constitution, the basis of the country's legal system currently in force, it is emphasized that the State is sovereign in exploiting and sustainable use of natural resources, including water resources. Nevertheless, this original version of the Constitution does not include any article concerning the accessibility of water by the population. It is not until 2017 that after a constitutional reform of Article 7 and in line with the provisions of the UN General Assembly in 2015, it is included that the State recognizes the constitutional right of everyone to have progressive and universal access to water and sanitation services (OECD, 2021a, p.34).

Under this initial reform and within the framework of the Constitution, the Peruvian government seeks to promote the sustainable management of water, which is recognized as an essential natural resource and constitutes a public source and patrimony of the Nation. Several laws, directives, supreme decrees, and technical standards at the national and local levels seek to regulate water management, the most important being the Water Resources Law (WRL). The Law in force since 2009 (Law No. 29338) legalizes the use and management of water resources. Also, it defines the different functions of governmental, civil, and private entities within the water sector. An exciting aspect of the WRL is that it incorporates a new legal framework for water as it establishes differences between surface water, groundwater, inland water, and associated assets (Méndez and Marchán, 2008; Arce, 2013).

Implementing the Water Resources Law is a decisive step towards integrated water resources planning, and some key policy decisions are being implemented at the national level. The first is the consolidation of the National Water Authority (ANA) role as the governing body and highest technical and regulatory authority of the country's National Water Resources Policy and Strategy. Likewise, the WRL refers to the Organic Structure of the National Water Authority, which includes the Local Water Administrations (ALA) at the basin scale, which depends on the Water Administrative Authorities (AAA) at the subnational scale (Rossi, 2010; Moscoso, 2011; FFLA, 2015).

An essential aspect of the ANA is that even though its multisectoral role at the national level is clear on paper, it is not in its actual implementation capacity. Indeed, although as the central agency seeks to overcome sectoral biases among all stakeholders, ANA continues to be a line agency of the MINAGRI. Therefore, this fact generates suspicions and questions from other ministries and private stakeholders about the impartiality of its actions, given the cross-cutting nature of water resource management. Another essential aspect of its role as a lead agency is promoting decentralized water management throughout the territory. Nevertheless, ANA incorporates the multiple water administrative authorities in its structure; in practice, many overlap activities and redundant actions. In addition to lacking an equitable distribution of adequate resources and allocated capacities, this aspect significantly reduces its effectiveness (OECD, 2021a, pp. 51-52).

The second significant policy decision detached from the WRL is creating the National Water Resources Management System (SNGRH). It is a decentralization platform that brings together principles, norms, and actors for the integrated and participatory management of water resources, seeking to promote their sustainable use, conservation, and quality. The SNGRH is led by the ANA and comprises all public sector institutions (ministries, regional and municipal governments) and users with competencies and functions related to water management, including the organized population. It should be clarified that the SNGRH incorporates civil organizations as the Law establishes the priority of the population over other sectors (industrial, agriculture, among others) in water use (Méndez and Marchán, 2008; Rossi, 2010; Moscoso, 2011; Arce, 2013). Two essential tools are established as part of the SNGRH, the National Water Resources Policy-Strategy, and the National Water Resources Plan. The first is essentially the planning tool through which management instruments should be developed at different scales (national, subnational, and local) and is based on five pillars that seek to meet the current demand, quality, availability, and efficient use. Among them are the correct management of quantity, quality, opportunity, culture and education, and adaptation to climate change. The second important tool within the SNGRH, the National Plan, is the planning instrument for implementing the first one, based on the diagnoses at the basin level and emphasizing the financing gaps that need to be filled (OECD, 2021a, p.36).

As mentioned previously, there are already doubts about the effectiveness of ANA's function as the governing body at the national level. Nevertheless, these uncertainties also extend to the National Water Resources Management System as an effective multisectoral platform. The questions are focused mainly on the low frequency of meetings with prolonged gaps throughout the year and an unbalanced participation level among the stakeholders. These doubts also translate into a lack of coherence in the public policies of the different ministries that make up the SNGRH, which in most cases are not aligned with the water policies promoted by the platform (OECD, 2021a, p.35). However, one of the most relevant aspects of the research is that with the Law of Water Resources, Peru establishes principles that govern the use and management of water. Thus, the third crucial policy decision is recognizing the 159 river basins as local management units and adopting Integrated Water Resources Management (IWRM) as the central axis. It should be recalled that IWRM is an internationally accepted approach and has been discussed in Chapter 2.

According to Article 6 of the WRL, integrated water resources management seeks to coordinate water use and development from a multisectoral vision within a river basin. The WRL understands a river basin as the natural territorial unit of planning and management that contemplates the interaction between soil, water, and vegetation as well as the social (population) and economic (industry) system that develops within its boundaries. The latter (socio-economic system) has no physical limits within the basin. However, its development depends mainly on the supply, quality of water, and spatial distribution of resources. This dissociation between natural boundaries and the absence of socio-economic boundaries has the most significant impact on water availability, mainly since watersheds are usually composed of more than one political-administrative region. In other words, the natural division of river basins does not usually coincide with the political-administrative limits of the territory and, therefore, with the physical needs of each of the regions that make up the basin. This disconnection significantly complicates water management since it is not done equitably and often does not include the active participation of all stakeholders (FFLA, 2015).

Furthermore, under this integrated water management approach and considering basin management, the Basin Water Resources Councils (CRHC) were created in 2011 to improve multisectoral participation at the watershed level. The Councils are formed at the initiative of the regional governments and are integral bodies of the ANA, as previously mentioned. Their primary function is to be spaces for consultation at the local level where institutions and organizations of one or more regions that make up the basin can participate, plan, and coordinate the sustainable use of water resources within their area (FFLA, 2015). It is also important to mention some regulations that are relevant in water management. Among them is the approval of the Environmental Quality Standards (ECA) for water and their implementation, as well as the authorization of the Maximum Permissible Limits (LMP) for effluents from Domestic and Municipal Wastewater Treatment Plants (WWTP). Both will be analyzed in-depth later in the Water Quality Section in this chapter (Méndez and Marchán, 2008; Rossi, 2010; Moscoso, 2011; Arce, 2013).

4.4.2 Territorial and Hydrographic Administrative Organization of the CHIRILU Basin

Another of the fundamental aspects of the framework of water governance to understand institutional capacity is the organization at the hydrographic and territorial level of the Rimac-Chillon-Lurin Basin (CHIRILU) basin.

- Territorial Administration of the CHIRILU Basin

In terms of administration and, as previously mentioned, the political-administrative limits do not coincide with the hydrological administrative limits established by the WRL. The CHIRILU basin, under the political-administrative ordinance, covers an area of 8,050.1 km² from the central zone of the Andes Mountains (5,585 m.a.s.l.) to the central coast on the Pacific Ocean (0 m.a.s.l.). Nevertheless, it should also be noted that the Alto Mantaro River Basin (districts of Pasco and Junin-Yauli) is usually annexed to the basin's total area because it has the highest rainfall volume. Indeed, it is where the Service provider company has most of its decentralized water infrastructure to supply Lima. Thus, the territorial scope of the watershed covers a total area of 9,786.1 km², as can be seen in Figure 49 (ANA and GIZ, 2018). Politically, the watershed is located in the department of Lima, including the Provinces of Lima and Callao in the middle and lower area and the provinces of Canta and Huarochiri in the middle and upper zone. It also consists of the management areas of the Regional Government of Lima, the Regional Government of the Constitutional Province of Callao, and the Regional Government of Metropolitan Lima (FFLA, 2015). From a territorial perspective, although some literature considers the Chilca watershed south of Lima as part of the CHIRILU basin, the information found is not consistent, so it is not counted for research purposes (OA CHIRILU and GIZ, 2019).

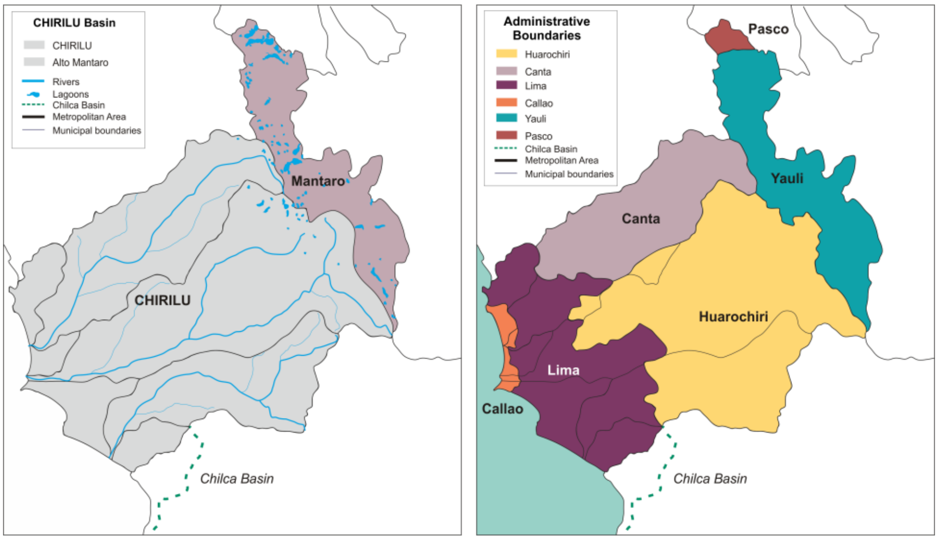


Figure 49: CHIRILU political-administrative regions

Source: Created by author, adapted from ANA and GIZ, 2018

From a social and demographic point of view, more than a third of the national population lives in the basin, with Metropolitan Lima (Lima and Callao) having the highest urban concentration in the lower basin, as shown in Table 6. On the other hand, according to INEI, the focus of the population with the least purchasing power is located in the upper areas of the watershed, with districts such as Huarochiri having 29% of its population below the economic poverty line and deficient essential services (OA CHIRILU and GIZ, 2019, p.33). Economically, the basin is home to several activities that account for 50% of the national GDP, including agricultural, industrial, commercial, service, mining, and energy activities. In addition, 84% of taxes are collected in this area (OA CHIRILU and GIZ, 2017).

Management	Department	Province	Districts	Population (inhab)
Metropolitan Lima Region	Lima	Lima	43	9,488 000.5
Lima Region		Huarochiri	27	63,400.0
		Canta	7	12,400.0
Callao Region	Callao	Callao	7	1,100 000.4
Total			**84**	**10,663 800.9**

Area of Influence (Alto Mantaro)	Junin	Yuli	4	13,222
	Pasco	Pasco	1	-

Table 6: CHIRILU's Basin population per region
Source: Created by author, adapted from CPI 2019; OA CHIRILU and GIZ, 2019; ANA and GIZ, 2018.

- <u>Hydrographic Administration of the CHIRILU Basin</u>

Under the hydrographic administration, the CHIRILU basin is situated in the Pacific watershed, as shown in Figure 50. On a national scale, the Pacific watershed shows the lowest water availability (only 2.1% of the total) and, contradictorily, the one with the highest concentration of inhabitants (65.9%) compared to the other two watersheds (Atlantic and Titicaca), as shown in Table 7. On the other hand, through the National Water Authority (ANA) and as previously mentioned, the country is divided into 14 Decentralized Bodies or also called Administrative Water Authorities (AAA), as well as 72 Local Water Authorities (ALA) at a basin scale.

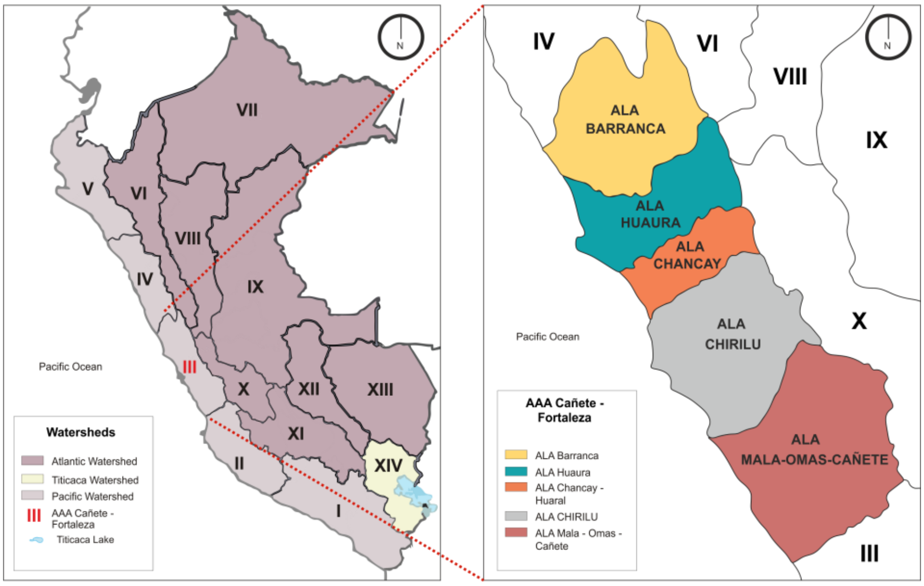


Figure 50: National hydrographic administration

Source: Created by author, adapted from ANA, 2009.

The CHIRILU basin belongs to the Cañete-Fortaleza Water Authority (AAA Cañete-Fortaleza), which covers 39,320 km² and covers the water needs of 98.6% of the Lima Region, 100% of the Callao Region, and part of Ancash and Junín. The AAA Cañete-Fortaleza contains 5 Local Water Authorities, in the case of the ALA Chillon-Rimac-Chillon (ALA CHIRILU), although it only covers 23.5% of the AAA Cañete-Fortaleza, it is the most important under its hydrographic administration (ANA, 2009).

Vertiente	Surface	Water Availability (%)	Population covered (%)	Basins	Administrative Water Authorities (AAA)
Atlantic Watershed	74.5	97.3%	30.7%	84	VI, VII, VIII. IX, X, XI, XII, XIII
Pacifico Watershed	21.7	**2.1%**	**65.9%**	62	I, II, **III**, IV, V
Titicaca Watershed	3.8	0.6%	3.2%	13	XIV

Table 7: National Watersheds System

Source: Created by author, adapted from ANA, 2009; ANA, 2019.

Internally, the CHIRILU basin comprises three individual basins, Chillon, Rimac, Lurin, and small sub-basins called Pacific sub-basins, as shown in Figure 51. The sub-basins receive drainage from other larger units upstream. In addition to these, as mentioned above, there is the influence of the Alto Mantaro basin in the upper zone. The Chillon, Rimac, and Lurin watersheds are bordered to the south by the Mala and Chilca river basins, to the north by the Chancay-Huaral river basin, and the Alto Huallaga inter-basin, and to the east by the Mantaro river basin. It is essential to mention that each basin is subdivided into nine smaller hydrographic units, as shown in Table 8. The largest surface area is the Rimac basin, representing 33.1% of the total, followed by Chillon with 22.3% and Lurin with 16%, respectively. The so-called Pacific inter-basins represent about 11% of the total area of the CHIRILU watershed (ANA and GIZ, 2018).

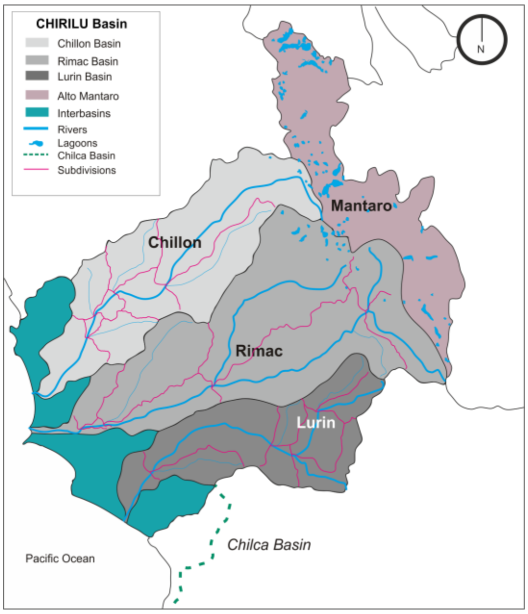


Figure 51: Distribution of the CHIRILU basin

Source: Created by author, adapted from ANA and GIZ, 2018

The Chillon Basin has an area of 2,181.5 km². A large part of its surface is located within the departments of Lima (Lima and Canta Provinces) and in the Constitutional Province of Callao. Its main river is the Chillon, whose source is located on the western flank of the Cordillera Viuda Mountain range and flows into the Pacific Ocean. The Rimac basin has an area of 3,240.6 km². A large part of its surface area is situated in the department of Lima (Lima and Huarochiri Provinces), and to a lesser extent, in the department of Junin (Yauli Province). The main river in the basin is the Rimac, which originates in the Nevado Pacay 132 km northeast of Lima and finally flows into the Pacific Ocean. As mentioned on many occasions, its flow is variable, with periods of low water and drought throughout the year. Lastly, there is the Lurin basin, whose area is 1,568.5 km². The main river in the basin is the Lurin, which originates in the snow-capped Surococha and flows 111.2 km to the Pacific Ocean. The specific hydrological characteristics of the three basins will be analyzed later in the UWMB section of this chapter (OA CHIRILU and GIZ, 2019).

Hydrographic unit		**Subdivisions**	**Area**		
			Km²		**%**
Chillon		Bajo Chillon	425.3	2,181.5	22.3%
		Medio Chillon	975.0		
		Alto Chillon	781.2		
Rimac		Bajo Rimac	181.1	3,240.6	33.1%
		Medio Rimac	2,654.0		
		Alto Rimac	405.5		
Lurin		Bajo Lurin	290.5	1,568.5	16.0%
		Medio Lurin	1,025.8		
		Alto Lurin	252.2		
Pacifico sub-basin		Various		1,059.5	10.8%
Mantaro	Yauli	Various	538.9	1,736.0	17.7%
	Conocancha	Various	586.1		
	Mantaro sub-basin	Various	611.2		
Total			**9 786.1**		**100%**

Table 8: Hydrographic units of the CHIRILU basin

Source: Created by author, adapted from OA CHIRILU and GIZ, 2019.

The non-coincidence between the political-administrative limits and the hydrological administrative boundaries of the basin causes a series of conflicts, especially in the regulatory and sanctioning areas between the different regional and municipal governments, as in the case of informal polluting activities. In the last decade, the country has recognized the need to implement land use planning processes with a watershed approach for efficient and effective decision-making in the face of water scarcity scenarios. However, nowadays, there is still no integrated process, only isolated efforts as in the Regional Government of Callao. The last effort document is from 2019, led by the Ministry of the Environment (MINAM). However, the results have not been published, possibly due to the high rotation of staff in public institutions, which in many cases results in the non-continuity of projects (OA CHIRILU and GIZ, 2019, pp. 36-37).

4.4.3 Main Stakeholders in CHIRILU Water Resources Management

The water governance system is composed of a vast network of actors where many functions and responsibilities are opposed, making its proper management even more complicated. According to their operations, stakeholders can be differentiated first: regulatory bodies, supervisors, operators, and users. On the other hand, their type of constitution can also be recognized, including public, private, and civil society stakeholders. The CHIRILU watershed network is mainly supported by public (governmental) actors who act at two management scales: multi-sectoral (national) and sectoral (local or focalized) (Rosazza, 2017).

- Regulatory Actors

Through the National Water Authority (ANA), the Ministry of Agrarian Development and Irrigation has more significant interference at the multi-sectoral scale. The ANA, as previously mentioned, is the main regulatory body that establishes the rules of the game at the national level, seeking a balance between water availability in the basin and the needs of the different productive sectors, including water demand for biodiversity conservation. It also establishes the rules to ensure water quality in natural sources and authorizes the development of hydraulic infrastructure, among other functions. The ANA manages in a decentralized manner in 72 Local Water Administration offices (ALA), grouped in 14 Water Administrative Authorities (AAA) that cover the scope of the 159 basins of the national territory (Rosazza, 2017).

In the case of the CHIRILU basin, it is under the general management of the Cañete - Fortaleza Water Administrative Authority and specifically through the Chillón-Rímac-Lurín Local Water Administrative Authority (ALA). The ALA aims at the operational management of water resources within the Chillon-Rimac-Lurin River Basin (CHIRILU). It emphasizes drinking water management, given the importance of domestic use in the basin (OECD, 2021b). On the other hand, the Ministry of Agrarian Development and Irrigation (MINAGRI), also through the General Directorate of Agricultural Infrastructure and Irrigation (DGIAR), plans and promotes investment for the construction of agricultural irrigation and drainage infrastructure, this due to the intensive demand of 22% of the water resources for agriculture in the basin (ANA and GIZ, 2018).

Then five other ministries also appear as regulatory bodies and, in essence, are the ones that define the rules of the game for operators, supervisors, and local users. The Ministry of Health (MINSA), through the General Directorate of Environmental Health (DIGESA), focuses on monitoring the water quality of the rivers that make up the basin, Chillon, Rimac, and Lurin. In contrast, the Ministry of Environment (MINAM), in addition to establishing the Maximum Permissible Limits (LMP) for the treatment and use of wastewater in the basin, also generates hydrometeorological information through the National Service of Meteorology and Hydrology (SENAMHI). The Ministry of Housing and Construction (MVCS) establishes and regulates the standards and technical specifications for drinking water, sewerage, and wastewater treatment systems within the basin. The Ministry of Energy and Mines (MINEM) focuses on regulating electric utility companies such as Enel Generación Perú (EDEGEL) for hydroelectric power generation and regulating mining operations. This aspect is essential for Metropolitan Lima, given its dependence on hydropower for domestic and productive energy generation. The Ministry of Economy (MEF) is responsible for financing infrastructure projects to improve management (OECD, 2021b).

At the level of intersectoral management in the CHIRILU basin, as is the case at the national level, the lack of coordination between the different ministries is one of the main obstacles to sustainable water management in the region, as it hinders the alignment of water management at the basin level with national policies.

- Operators

On the other hand, other actors that are differentiated by the role they play are the operators. They perform functions at both scales (multi-sectoral and sectoral) and are public, semi-public (a public company of private regime), or civil society representatives. At the multi-sectoral level are the Service Providing Companies (EPS); in the CHIRILU basin, the main one is the Lima Water and Sewerage Service (SEDAPAL). It is the most relevant water company at the national level because it covers the demand of the largest urban concentration in the country, such as Metropolitan Lima. Its primary mission is to provide sanitation services such as drinking water and sewerage (OECD, 2021b). The case of SEDAPAL is unique at the national level. Unlike other EPSs in the country with local governments as shareholders, ensuring an articulated work between both, in the case of Lima, SEDAPAL is a public company entirely owned by the State and in whose decision making no local government intervenes. In addition to this institutional control, SEDAPAL concentrates 80% of the water resources in the basin for domestic and productive use. SEDAPAL builds large infrastructure projects in the basin's headwaters to meet these demands, generating social pressures with the upper basin's local communities and financial problems due to the high maintenance costs involved (Robert, 2019).

It is precisely in these high and medium basin areas where, at the sectoral level, the Sanitation Services Administration Boards (JASS) exist. These are civil society operators that meet the demand for sanitation services from rural and peasant communities, which in many cases, as previously explained, use ancestral techniques such as amunas and irrigation canals to maintain harmony with the environment (Asociacion SER, 2013). Although the water management proposed through the Water Resources Law of 2009 is multi-sectoral, in the CHIRILU watershed, it faces a monopoly on the part of SEDAPAL in the face of the need for water resources for both domestic and agricultural use in the upper watershed. If not taken into account, this confrontation will only increase social pressures and represent another obstacle to sustainable water management in the region (Robert, 2019).

- Supervisors

The most important public actors exercising a supervisory function are the regional governments (GORE's) and district municipalities at the sectoral level. The GORE's primary function is to coordinate with ANA and among themselves (in case they share a basin as in the CHIRILU basin) to harmonize their policies and sectoral objectives and avoid conflicts of competence. They also exercise control and surveillance of water used for agricultural purposes, promote and execute irrigation projects and works, and in some cases are in charge of the operation and maintenance of the water infrastructure within their territorial limits. As previously mentioned, it is perhaps here where there is a significant inflection point in the coordination system. This factor is because the hydrological boundaries do not coincide with the administrative boundaries of the regional governments that make up the CHIRILU basin. Also, the realities and levels of development are different (OECD, 2021b).

In addition, other entities exercise the supervisory role at a multisectoral level that is important to mention, such as the National Superintendence of Sewerage Services (SUNASS) for water and OSINERGMIN for electricity service operators. In the case of SUNASS, its main objective is to regulate remunerations and tariffs for water management and rights and supervise the provision of sanitation and wastewater treatment services by the EPSs, as is the case of SEDAPAL. Amid this operator-regulator relationship, there are several disputes. On the one hand, SEDAPAL establishes the need to increase sanitation tariffs for residential users by up to 8.7% annually to generate new projects and optimize the service. This increase, according to SEDAPAL's argument, is because 99% of residential tariffs are subsidized with an average benefit of US$0.30 per cubic meter ($m^3$), equivalent to 36% of the real tariff value (El Peruano, 2020). On the other hand, SUNASS states that, in effect, tariff regulation is necessary but should be done through a system of cross-subsidies, i.e., delivering the benefit of the subsidy to the families that need it (lower-income families) (SUNASS, 2017).

On the other hand and concerning SEDAPAL's intervention under severe social pressures in the headwaters (upper basin), SUNASS in 2015 ordered payment for ecosystem services (PSE), allocating 1% annually SEDAPAL's total collection. The main goal is to create a fund to repair and conserve ecosystems and environmental services in the Mantaro and Rimac rivers. Although SEDAPAL has collected more than USD 26 million, unfortunately, it has not yet been operationalized due to institutional bottlenecks and diverse questions about the use of the revenues collected from operations, especially from the industrial sector (OECD, 2021b, p.186).

- Users and Civil Stakeholders

There is also a group of private, academic, and non-governmental actors who, although more representative today, still do not play a transcendental role in water governance decision-making. It is worth mentioning that the linkage between these organizations adds much to a better scientific study and strengthening of capacities, information, and resources for sustainable management of the basin. The first steps have already been taken. Organizations such as AQUAFONDO has been working with peasant communities in the middle and upper basin for the recovery of amunas and ancestral canals, or the case of GIZ that through projects such as PROAGUA II, provides advice and institutional capacity building for better sanitation and wastewater treatment (AQUAFONDO, 2020; GIZ, 2018). It is also important to highlight in civil society organizations the so-called Juntas de Regantes. They, hand in hand with district municipalities, regulate the maintenance of irrigation canals in the urban fabric and supply water for watering public green areas. Figure 52 shows a graphic illustration of the many actors involved in water resources management and their interrelationship.

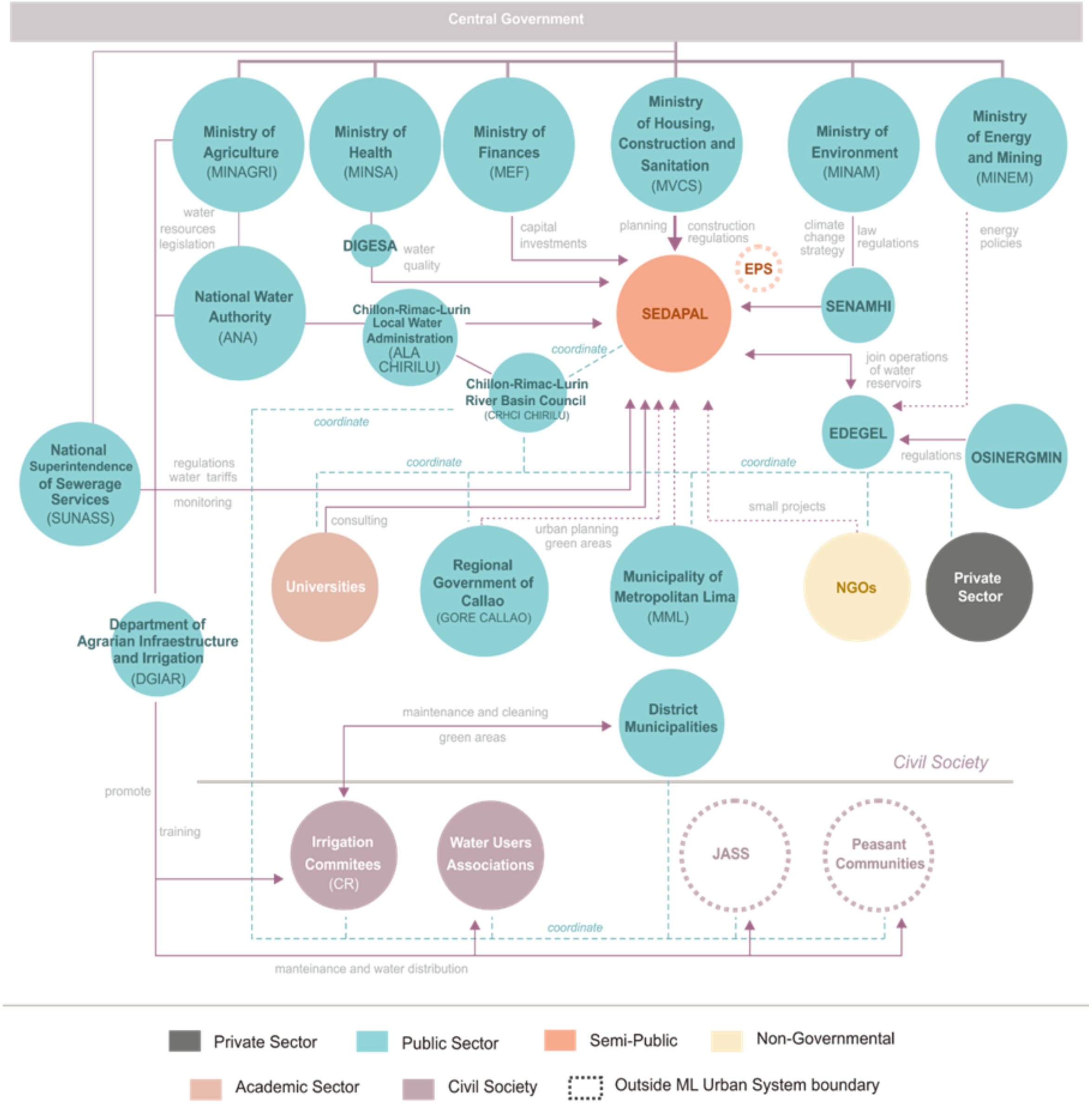


Figure 52: Institutional framework of water management in Lima/Peru

Source: Created by author, adapted from Schütze *et al.*, 2018.

4.4.4 Council CHIRILU

In order to improve multisectoral participation at the basin level, the Chillon-Rimac-Lurin Basin Council (CRHC CHIRILU) was created in 2016, which is essentially a space for consultation between the multiple stakeholders in the region linked to the integrated management of water resources. At the national level, the CRHC CHIRILU was the last Council created after a long coordination process that took five years between representatives of the three regions that make up the basin (Metropolitan Lima Regional Government, Lima Provinces Regional Government, Callao Regional Government). This slowness in its formation was primarily influenced by its stakeholders' diverse and conflicting interests, making its representativeness, levels of coordination, and functioning very difficult. Even though its creation has been the product of a cumbersome process, the Council is indeed the best example of an attempt at dialogue and coordination of needs, projects, claims, as well as planning and coordination of sustainable water use in the basin among the different stakeholders of the region. Therefore, eight Working Groups with specific objectives have been created, as shown in Table 9. (ANA, 2020).

However, the Council lacks operational instruments, but above all shared policies and objectives, since its primary planning tool, the Basin Water Resources Management Plan (PGRHC), is still pending approval. Another significant shortcoming that the Council has yet to remedy is the diversity of low quality, poorly updated, and concise data that each actor manages at the dialogue processes, mainly due to the lack of human capacity and technical tools to fulfill this role. Given this, creating the Chillon Rimac Lurin Water Observatory Working Group, whose objective is to consolidate and allow the exchange of information, is an extremely promising and valuable initiative for more effective and efficient decision-making. On the other hand, although all stakeholders have a stronger voice, those representing the minority, such as the private sector, academia, and civil society, still do not have balanced participation, active involvement, or empowerment. One of the main reasons is the institutional monopoly and conflict of interests that persist in the basin. From the economic point of view, the Council does not have an independent budget or institutional fund because it depends strictly on the ANA, which reduces its capacity for action and investment in the basin and diminishes its power for a concerted effort for the common good. After all, the Council must accept the financing and prioritization schemes that the stakeholders determine necessary to cover, in most cases, individual and not collective needs (OECD, 2021b).

Working group	Main Objective
Multisectoral Working Group of the Chillon River Basin	Coordinate measures to solve the diverse problems of the watershed, like encroachment on the marginal strip, solid waste dumping, or wastewater discharge into the river and irrigation canals.
Water Culture Working Group	Plan and coordinate inter-institutional actions through integrated management that promotes water culture within the Council in the face of watershed problems.
Natural Infrastructure and Water Conservation Working Group of the Chillon Rimac and Lurin River Basins (INCA)	Design tools to promote, coordinate and implement actions for the development of natural infrastructure within the scope of the Council, as well as address the main technical challenges associated with the management of water ecosystem services.
Working Group on Water Availability Development Plan (PADH)	Plan and coordinate the sustainable use of water in the interregional basin.
Multisectoral Working Group of the Santa Eulalia River sub-basin	Through integrated management, plan, coordinate, and implement inter-institutional actions to achieve sustainable water resource use in the Santa Eulalia sub-basin.
Multisectoral Working Group of the Lurin River Basin	Plan, coordinate, and implement inter-institutional actions to achieve sustainable use of water resources in the Lurin river basin through integrated management.
Multisectoral Commission for the Recovery of the Quality of Water Resources in the Rímac River Basin	Coordinate, establish, determine, carry out follow-up actions, promote the necessary investments and issue technical reports to recover the quality of water resources in the Rimac river basin.

Chillon Rimac Lurin Water Observatory Working Group	Generate information for the GIRH in the Chillon, Rimac, and Lurin basins, and contribute to their adaptation to climate change.

Table 9: CHIRILU Council's Working Groups

Source: Created by author, adapted from ANA, 2020; OECD, 2021b.

4.5 Urban Metabolism of ML

Given the complexity of cities, with particular emphasis on semi-arid environments, a better understanding of the urban water cycle and the metabolic processes of the urban environment is necessary to ensure transitoriness towards water sustainability. In this sense, this section seeks to answer: Which water flow has the most significant potential for improvement in the water system of Metropolitan Lima?

Throughout Chapter 2 (Theoretical Framework), different existing urban water assessment approaches vital for a better understanding of the metabolism of the urban environment were presented. Compared to methods such as Life Cycle Assessment (LCA), Integrated Water Cycle Modelling (IWCM), Material Flow Analysis (MFA), UWMB presents a more promising scheme by focusing on the urban water cycle and contemplating both natural and anthropogenic flows into and out of the defined boundary. Although water resources management is based on watershed management in the Peruvian scenario, for the research, only the ML is covered as defined in the Methodology section (see Chapter 1). Nevertheless, the application of UWMB at the watershed level in the future could provide a more robust view of the hydrological system of which the city is a part.

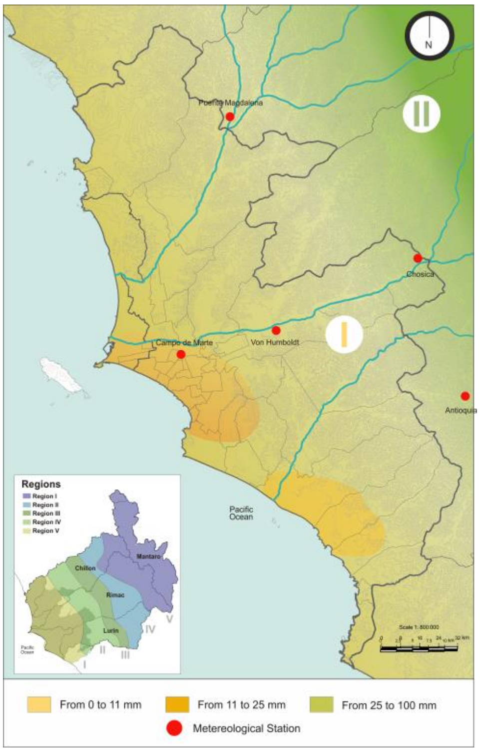
For data validation, results from other UWMB studies applied around the world are used, such as the case of Australian cities (Sydney, Melbourne, South East Queensland (SEQ) and Perth), Cape Town, and Bangalore in India (Kenway, Gregory and McMahon, 2011; Paul *et al.*, 2018; Hegyi, 2019). The latter has many similarities with Metropolitan Lima. From the hydrological aspect, it presents, as in the Peruvian case, low levels of rainfall (contrary to the case of Australian cities), also from the demographic aspect (9.5 million inhabitants), territorial and socioeconomic being part of a developing country. It is essential to point out that in both cases, the data is not recent. In the first case (Australia), it is from the period 2004-2005, and in the case of Bangalore, it is from the period 2014-2015, which could make the comparison not powerful. Nevertheless, the results give a complete picture of the hydrological performance of the city, a crucial aspect in the elaboration of a water-sensitive strategy.

4.5.1 Precipitation (P)

Quality of data: Medium

Precipitation or pluviometry, which includes other states of rainfall like snow or dew, is one of the essential natural hydrological flows in the urban metabolism of an area since it directly influences the amount of decentralized water coming from rainwater reservoirs, flows to groundwater, stormwater runoff, and potentially evapotranspiration (Kenway, Gregory and McMahon, 2011, p. 698). In the case of Lima, as well described by Cieza de Leon in 1553, *"Neither rains, nor lightning nor flashes of lightning, no thunder is seen, but the sky is always serene and stunning."* However, there is a large amount of *"water vapor,"* as Hipolito Unanue called the city's characteristic fog. Precipitation is closely associated with atmospheric thermo-convection processes; the non-occurrence of such pluviometric mechanisms explains the absence of significant aqueous rainfall (Capel, 1999, pp. 25-27).

In 2013, the Ministry of the Environment (MINAM) established that within the CHIRILU hydrological basin, five regions had very heterogeneous physical values since they had different soil and topographic characteristics that directly impacted precipitation levels. In this sense, the higher parts are the ones that present higher intensity levels. Under this analysis, only Region IV and Region V are within the territorial limits of Metropolitan Lima. Indeed, only these data are considered for the calculation of UWMB. According to the Watershed Observatory and SENAMHI, in 2016, the average rainfall in Metropolitan Lima was 7.5 mm. It should be noted that that year (2016) was extremely dry at the national level. In comparison, 2017 was an extremely wet year (11.3 mm per year) due to the effects of the El Niño phenomenon (INEI, 2018). Data from 2018 and 2019 also show an increase in precipitation reaching 26.4 mm, showing variations related to climate change. However, the most considerable amount of valid and high-quality data obtained is the interval between 2016-2017 and offers two heterogeneous scenarios that enrich the analysis (INEI, 2020a). It should be mentioned that precipitation levels are not homogeneous throughout the territory of ML, as shown in Figure 53. Thus, in flat areas, levels do not exceed 5 mm. On the der hand, in points of medium to the steep slope, levels can reach 40 mm due to high concentrations of humidity (between 80% and 100%) in addition to the generation of haze zones between 359 and 659 meters above sea level (Paniagua, 2016; León, Ocola and Rojas, 2019, p.5). The conversion factors showed in the Methodology section (see Chapter 1) were used for the calculation. Then:



Annual precipitation 2016 -2017 LM: 9.4 mm
Area of ML: 2 819 km^2
1 mm rainfall = 1 l/m^2
9.4 mm = 9.4 l/m^2
2,819 000 000 m^2/ 1 m^2 = x l / 9.4 l
x = 26,498 600 000 l = 26.49 Gigaliters
Applicable Data: 26.49 Gigaliters

Figure 53: Precipitation levels in ML
Source: Created by author, adapted from INEI, 2020a.

4.5.2 Centralized Supply (C)

Quality of data: High

Centralized sources are the second most crucial hydrological flow after precipitation in the UM. They originate outside the urban area and enter the city boundary through natural rivers or streams. Although this component was not initially contemplated in the original equation, it would later be included. Also, water collected from aquifers and desalination plants would be added (Kenway, Gregory, and McMahon, 2011, p.697).

In the case of Lima, as mentioned in several sections in the research, natural water flows enter the urban environment through the three rivers that make up the CHIRILU basin. The Rimac River has the most significant quantities, with natural volumes up to 2.7 times more than Chillon and ten times more than Lurin, as shown in Figure 54. Another relevant aspect is the variability due to its condition as a seasonal river. In this sense, factor C includes, in addition to the natural sources, the regulated sources that supply water to the Rimac River during low water periods due to lack of precipitation in the upper zone of the basin. This source is based on water collected in SEDAPAL dams and lagoons that do not offer their maximum capacity due to difficulties in their maintenance system. For example, the Yuracmayo Dam has a volume of 48.30 hm^3, and the 15 regulated lagoons in Santa Eulalia are up to 77.00 hm^3. However, the contribution to the Rimac River is 97.7 Hm^3, almost a fifth of its natural flow. The Chillon River also has the upstream infrastructure to regulate its flow during low water levels, with a capacity of 21 Hm^3; however, there is no consistent information on its operation, so it is not considered in the analysis. On the other hand, and as established in the previous section, the Alto Mantaro basin is vital to CHIRILU because of the amount of water it transfers to the Rimac River. In this sense, the Marcapomacocha system contributes 252.9 Hm^3, given the high levels of precipitation in the area (ANA and GIZ, 2018, pp. 25-49).

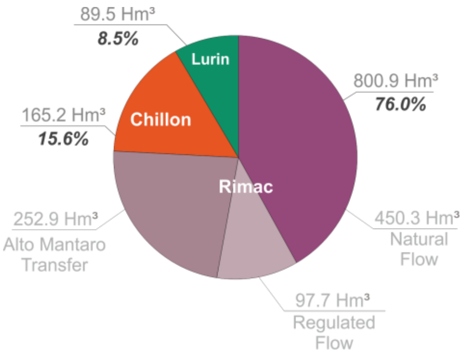


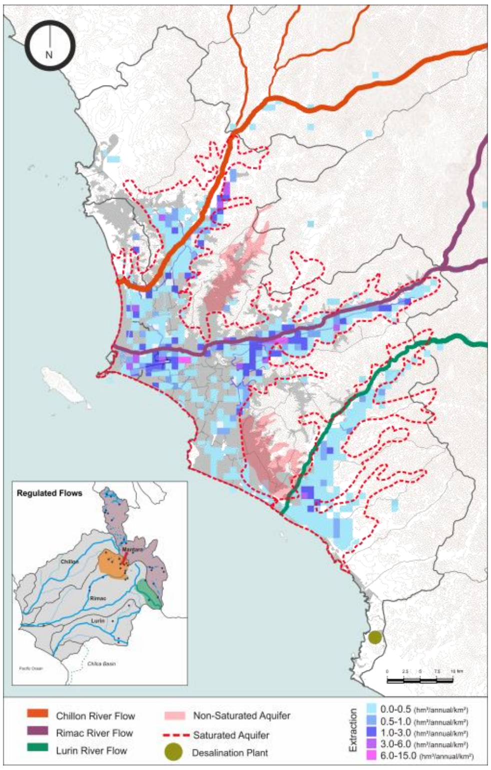
Figure 54: Distribution of Lima's centralized water system

Source: Created by author, adapted from ANA and GIZ, 2018; OA CHIRILU and GIZ, 2019.

While these regulated supplies would fit better in the group of decentralized sources (D) due to their anthropogenic characteristics outside the urban boundary, the fact is that unlike many cities in the world, such as Mexico City and its export of water from the Lerma-Balsas and Cutzamala basins, in the Peruvian case these flows are not connected to the Lima system through pipes outside the rivers. On the contrary, it is through them that the water enters the city (Tortajada and Castelán, 2003). This gap of an external infrastructure implies a city's dependence on water from the rivers, whether from natural or regulated sources, increasing its vulnerability to external factors (natural, anthropogenic, or climatic) along the watershed that could leave the city without water resources.

Another element of factor C is groundwater flows, as shown in Figure 55. In this case, in Lima and according to the study carried out by the ANA at a depth of 10 meters (groundwater levels range from 600 m in the upper parts and less than 20 m along the coastal zone) and using a conservative storage coefficient (5%), the aquifer supply is 433.3 Hm³, where 330.2 hm³ is from the Chillon-Rimac and 103.1 hm³ for the Lurin aquifer. Based on the information provided by SEDAPAL, ANA determined that the 270 active wells owned by the state-owned company extract 8m³/s for the Chillon-Lurin aquifer and 1.1 m³/s for the Lurin aquifer. For the final calculation, ANA, according to a theoretical estimate of groundwater supply based on exploited flows, increases 7.6% of the total amounts. It is understood that this assumption is because there are no external measurements to confirm the data offered by the state company and thus establish if the groundwater is being managed sustainably. Performing additional measures in the future will avoid overexploitation and salinization by the marine intrusion, problems of which there are already records (ANA and GIZ, 2018, pp. 28-49).

On the other hand, during 2020, the construction of the new Desalination Plant in the South of Metropolitan Lima - PROVISUR Project was completed. Nevertheless, its scale of intervention is small. Also, it has only been in operation for months, outside the 2016-2017 period established for the calculation, which is why the data is not contemplated (Fernández, 2021). However, it is worth mentioning that according to statements from central government agencies, the desalination plant seeks to produce 400 liters of water per second to supply 100,000 people in the districts of Pucusana, Punta Hermosa, San Bartolo, and Punta Negra. Meanwhile, the project is being questioned for its high energy consumption, environmental impact, and high prices, as desalinating water costs up to six times more than making surface freshwater potable (Ziegler and Morales, 2020). The conversion factors showed in the Methodology section (see Chapter 1) were used for the calculation. Then:



Natural surface flows:
Rimac: 450.3 Hm³ = 450.3 GL
Chillon: 165.2 Hm³ = 165.2 GL
Lurin: 89.5 Hm³ = 89.5 GL
Subtotal: 705 Gigaliters

Regulated flows and Water Transfer:
Rimac: 97.7 Hm³ = 97.7 GL
Alto Mantaro: 252.9 Hm³ = 252.9 GL
Subtotal: 350.6 Gigaliters

Groundwater natural flows:
Rimac-Chillon Aquifer: 271.6 Hm³ = 271.6 GL
Lurin Aquifer: 37.4 Hm³ = 37.4 GL
Subtotal: 309 Gigaliters

Applicable Data: 1364.6 Gigaliters

Figure 55: Centralized Supply in ML
Source: Created by author, adapted from ANA and GIZ, 2018; OA CHIRILU and GIZ, 2019.

4.5.3 Decentralized Supply (Dg)

Quality of data: Low

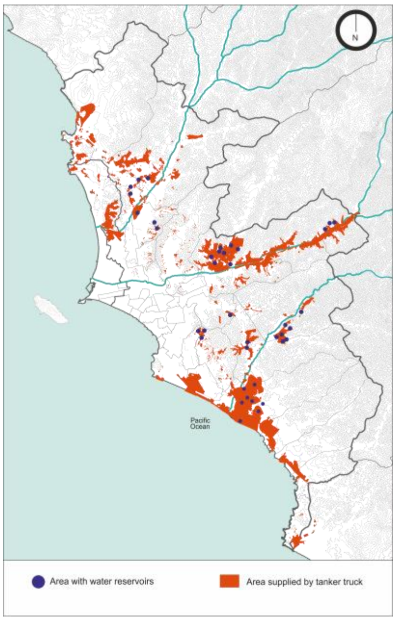
Decentralized sources, usually applied on a small scale, encompass various water harvesting measures and techniques. According to the UWMB, the three most common systems are rainwater harvesting through tanks, groundwater supply through private pumping wells, and surface water supply through private tanker trucks. In the case of Lima, there is some variation in the systems since rainwater harvesting is almost nonexistent, and there is no information on subterranean extraction wells due to their private nature. As a result of the investigation, two decentralized sources were found, as shown in Figure 56, although their values are not significant in the balance. It should also be mentioned that the information found is not sufficiently concise and is purely based on estimates.

The first source is based on the EU-funded Water Supply Project for informal settlements of Lima (APPJ) 1993-2001, through which 204 water reservoirs were built trying to fill the water gap in the absence of water and sewage connections for more than 48,000 families (Bonfiglio, 2002). From the last update of the project in 2012, it is known that only 120 reservoirs are still active; the rest managed to connect to the formal household water and sanitation network. The reservoirs have a daily production of 6,000 m^3 (filled with water from tanker trucks); however, this data and the status nowadays of the infrastructure require an update (Acevedo, 2012).

Another decentralized and prevalent source in the peri-urban areas of the city is the supply from tanker trucks. These draw water from SEDAPAL's subterranean wells and informal private suppliers (artesian wells), which generally do not meet sanitary standards and, as previously mentioned, increase the cost per liter. Nowadays, approximately 212 trucks supply water in the capital with a daily capacity of 36,000 liters each. SEDAPAL also has a fleet of 41 cisterns, but these only operate in case of emergencies in the city (ANDINA, 2021b; Ziegler and Morales, 2020). The conversion factors showed in the Methodology section (see Chapter 1) were used for the calculation. Then:

Figure 56: Decentralized Supply in ML

Source: Created by author, adapted from Acevedo, 2012; Bonfiglio, 2002



Decentralized Sources of Reservoirs

Reservoirs = 6,000 m^3 * 365 = 2 191,453 m^3/year

Reservoirs : 2.19 Hm^3/year

Decentralized Sources of Tanker Trucks

Truck= 36m^3*365 = 13,140m^3/year * 212 = 2,785 680 m^3/year

Trucks: 2.78 Hm^3/year

Subtotal = 4.97 Hm^3 = 4.97 GL

Applicable Data: 4.97 Gigaliters

4.5.4 Centralized Recycled Water (Rw)

Quality of data: High

As previously mentioned in several sections, some of Lima's municipal green areas and agricultural zones are watered by recycled water. According to what was established by the ANA, of the total collected wastewater that receives secondary or tertiary treatment in Lima (2 787.3 l/s), only 33.8% is reused for irrigation of agricultural areas and 16.9% for irrigation of green spaces. The remaining flow ends up in the ocean without a previous reuse process (ANA and GIZ, 2018). Over this data, a precision was made by comparing it with other sources, finding that the total water receiving secondary treatment is 2,801.4 l/s and in the case of tertiary treatments, 129.5 l/s making a total of 2,930.9 liters per second, as shown in Figure 57 (Rossi, 2010, p.8; Moscoso, 2011; Olivos, 2018). In this sense, using this number, the reuse percentages as mentioned earlier have been applied.

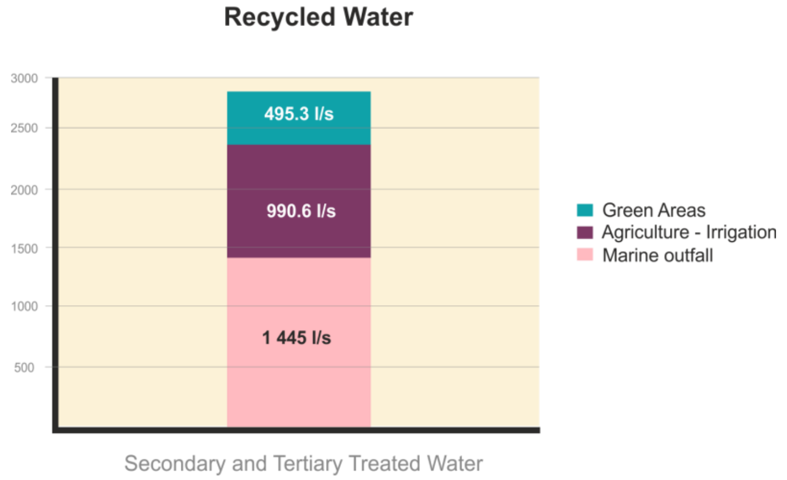


Figure 57: Recycled Water in ML

Source: Created by author, adapted from ANA and GIZ, 2018; Rossi, 2010; Moscoso, 2011.

According to Peruvian regulations, the purpose of secondary treatment is to reduce the organic matter present in the wastewater once the pretreatment and primary treatment phases have been completed. The secondary or biological treatment has been designed, taking as an example the biological process of self-purification that occurs naturally. Indeed, the biological treatment is the oxidation of biodegradable organic matter using bacteria to accelerate a natural process and subsequently avoid the presence of pollutants and the absence of oxygen in the water bodies. According to the information collected, 28 plants carry out the secondary treatment in Lima, and the most common aerobic processes are aerated lagoons and activated sludge. In addition, 16 of these plants are managed by SEDAPAL, while municipal governments and private entities manage the others. On this point, it is also important to emphasize that the plants operate at only 57% of their actual design capacity (Rossi, 2010, p.8; Moscoso, 2011; Olivos, 2018).

On the other hand, the objectives of tertiary treatment are to eliminate the organic load remaining from secondary treatment, eliminate pathogenic microorganisms, eliminate undesirable color and odor, remove detergents, residual phosphates, and nitrates, which cause foaming and eutrophication, respectively. According to Peruvian regulations, chlorination is part of the tertiary or advanced treatment used to achieve purer water. The purpose is to meet the effluent water quality standard of the treatment plant, not to contaminate the recipient or make it suitable for reuse, as the case may be. Only 11 plants in the city carry out these procedures (tertiary), and of the total, only one is managed by SEDAPAL. In addition, the plants operate at only 67.5% of their actual design capacity, mainly due to structural failures during construction caused by the misappropriation of funds by public authorities and institutions (Rossi, 2010, p.9; Ziegler and Morales, 2020). A complete picture will be reviewed later when analyzing the elements of Lima's OUTPUT (Wastewater). The conversion factors showed in the Methodology section (see Chapter 1) were used for the calculation. Then:

Recycled wastewater
Irrigation of Public Green Areas: 495.3 l/s
Agriculture: 990.6 l/s
Subtotal=1,485.9 l/s

Where:
1,490 l/s =1.490 m^3/s = 46.98 Hm^3

Applicable Data: 46.98 Gigaliters

4.5.5 Wastewater (W)

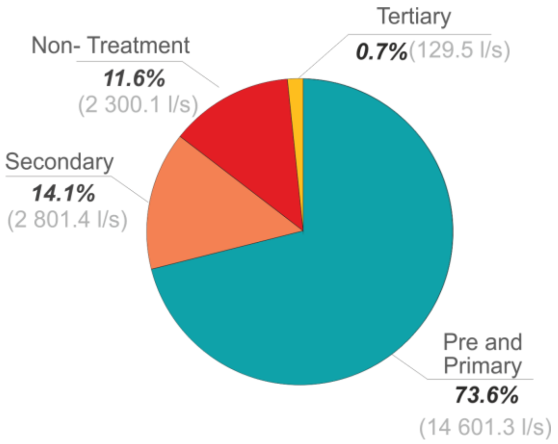
Quality of data: High

In Lima, most of the water produced by domestic, industrial, productive, and other sectors is collected by SEDAPAL and then treated in wastewater treatment plants (WWTP) or directly diverted back to the rivers' tributaries finally ends up in the Pacific Ocean. After cleaning the contaminated water through mostly preliminary or primary treatment processes, it can be safely discharged into the environment. Although, as discussed in the next section (Water Quality), in some cases, it does not meet the minimum requirements showing the presence of fecal or thermotolerant coliforms, among others well above the maximum limits allowed by Peruvian regulations.

There are 42 plants in the city of Lima, managed by SEDAPAL (20), the Municipality of Lima (2), local municipal governments (15), and five by private institutions. Nevertheless, more exist but are not included in the analysis due to a lack of information. According to ANA, the total amount of wastewater collected in Lima is 19,832 l/s (19.8 m^3/s), of which 83.9% receive preliminary and primary treatment, 13.8% receive secondary treatment, a smaller amount receives tertiary treatment (0.2%), and 2% does not receive treatment (ANA and GIZ, 2018). However, these values have been adjusted to the data collected from the existing plants in Metropolitan Lima and found that they are in the order of 73.6% (14,601.3 l/s) receive preliminary and primary treatment, 14.1% (2,801.4 l/s) secondary, less than 1% (129.5 l/s) tertiary and 11.6% do not receive treatment. The mismatch for what ANA announced, especially concerning the percentage of water that does not receive treatment (2% vs. 11.6%), could be answered that the plants only operate at 69% of their actual total design capacity and not 100% as would be expected. Therefore, this means that they are processing 17 531 liters per second, as shown in Figure 58 (Rossi, 2010; Moscoso, 2011; ANA and GIZ, 2018, p.8; Olivos, 2018).

Figure 58: Wastewater in ML

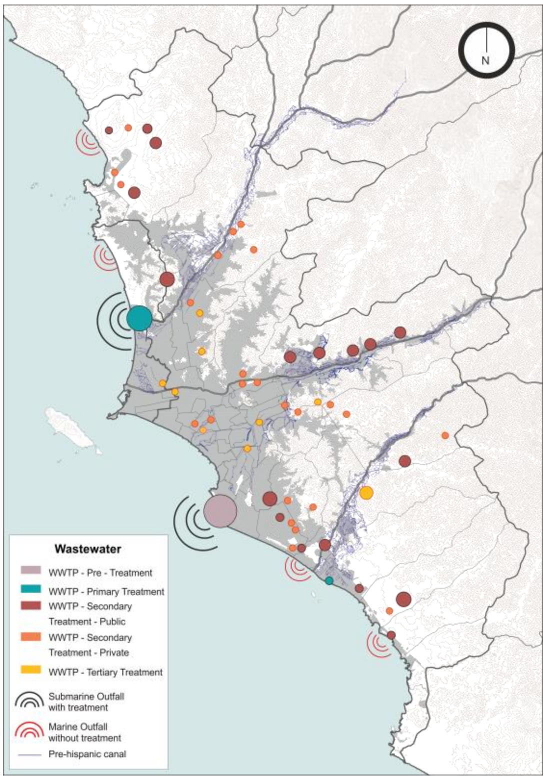
Source: Created by author, adapted from ANA and GIZ, 2018; Rossi, 2010; Moscoso, 2011.



During the last decade, the situation in the framework of wastewater treatment coverage in Lima has mainly changed. In a timeline, by mid-2011, there was a deficit in wastewater treatment with an alarming range in 41 Plants (between public and private) of only 17% of the wastewater produced daily in Lima. It is worth mentioning that according to the information found, the flow of the treatment plants at that time was 3,178 l/s, of which 2,810 l/s corresponded to the 19 plants operated by Sedapal (Moscoso, 2011, p.12). The projection was that by 2024 the figure of untreated wastewater would double, so the Peruvian government decided to finally promote two previously shelved but emblematic projects for the city through SEDAPAL: WWTP Taboada and WWTP La Chira.

The Taboada Wastewater Treatment Plant, located in the province of Callao, required an investment of US$ 172 million and included a primary treatment system and a submarine emitter. It produces an effluent with an average flow of 14 m³/s and a maximum of 20.3 m³/s, serving a population of more than 4.3 million inhabitants (equivalent to 27 districts), which at the time of its commissioning represented 56% of the inhabitants of Lima and Callao and 72% of the wastewater of Metropolitan Lima (Tedagua, 2014, pp. 81-82). The La Chira Wastewater Treatment Plant and Submarine Outfall (WWTP La Chira) project aim to treat wastewater from six districts of the city of Lima (Villa El Salvador, Miraflores, Barranco, Chorrillos, Surco, and San Isidro) and the final disposal of this and other waste (solids, sludge, among others). Before the project, water from this area of Lima was discharged into the ocean without treatment. The plant, which has an average water treatment capacity of 6.3 m³/s and a maximum level of 11.3 m³/s, is located in the district of Chorrillos and serves about 2.5 million people (Salvador *et al.,* 2019, p.7). Both were put into operation between 2013-2015, meaning an increase in wastewater treatment coverage for Metropolitan Lima Nevertheless, it is still insufficient since the concentration is only in primary treatment and not in those necessary for water recycling, such as secondary and tertiary. In comparison, in Germany, 0.1% of total wastewater receives only mechanical treatment (preliminary or primary), and 98% goes through a biological treatment process with selective removal of nutrients that allow subsequent reuse (BMU, 2019).

From a spatial aspect of the total Wastewater Treatment Plants in Lima, 69% are located in the city's north (14) and south (15), as shown in Figure 59. This response mainly to being flatter areas unlike the east of ML and with greater availability of areas, unlike the city's center. Towards the east of the ML, there are five plants (11.9%), and eight are located in the center, representing 19% of the total (Rossi, 2010, p.8; Moscoso, 2011; Olivos, 2018). One aspect to highlight is that more than 35% of the plants are located on or very close to the network of pre-hispanic irrigation canals. In the Lurin valley, five plants are located under this condition, 7 in the Rimac valley and 3 in the Chillon valley. Although there is no physical connection today, it could be an exciting aspect to promote in the future. For the analysis of UWMB Outputs, the values associated with the recycling of wastewater analyzed in the previous section have been discounted since they do not count as an output of the system when they return. This value also includes the 7.3% of the water that is not recycled after receiving secondary or tertiary treatment and returns to the influent. The conversion factors showed in the Methodology section (see Chapter 1) were used for the calculation. Then:



Treated Wastewater:
Secondary and Tertiary Treatment: 1,445 l/s
Primary - Preliminary Treatment: 14,601.3 l/s

Marine outfall:
Untreated: 2,300.1 l/s (11.6%)

Subtotal: 18,346.4 l/s

Where:

18,346 l/s = 18.346 m^3/s = 578.56 Hm^3

Applicable Data: 578.56 Gigaliters

Figure 59: Wastewater Treatment Plants in Lima

Source: Created by author, adapted from ANA and GIZ, 2018; Rossi, 2010; Moscoso, 2011.

4.5.6 Natural hydrological outflows (Rs, G, and ET)

Quality of data Rs: Low / Quality of data G: High / Quality of data ET: High

Surface runoff is the water that flows through soils in the event of precipitation. It depends mainly on the type of surface, with paved areas in urban areas and areas on slopes or rocky soil having the most meaningful influence on increasing the quantity and velocity of runoff by significantly reducing the absorption capacity of the ground. On the other hand, green surfaces and agricultural areas represent a lower volume of runoff. These covers directly affect groundwater recharge, lower in urban areas and higher in areas with blue and green infrastructure. Evapotranspiration is the flow from water evaporation from land surfaces and plant transpiration (Hanson, 2016).

In order to calculate runoff, the structure of the total area of Metropolitan Lima (2,819 km²) has been used, discounting the water bodies and islands, as well as the coefficients shown in the Methodology section (see Chapter 1). In Groundwater recharge and evapotranspiration, the data established by the National Water Authority is used (ANA and GIZ, 2018, p. 49). Then:

Surface Runoff:
Urban Area: 57,808.00 ha =578.08 km²
578.08*0.7/10= **40.47 Gigaliters**
Roads Areas: 23,839.00 ha = 238.39 km²
238.39*0.95/10= **22.65 Gigaliters**
Green Areas: 29,429.00 ha = 294.29 km²
294.29*0.15/10= **4.41 Gigaliters**
Agricultural Areas: 11,099.00 ha. = 110.99 km²
110.99*0.1/10= **1.11 Gigaliters**
Coastal Areas: 2,527.00 ha. = 25.27 km²
25.27*0.58/10= **1.47 Gigaliters**
Mountain Areas: 154,203.00 ha. = 1542.03 km²
1542.03*0.3/10= **46.26 Gigaliters**
Subtotal: 116.36 GL

Groundwater recharge: 295.9 hm³
Subtotal: 295.90 GL

Evapotranspiration: 251.1 hm³
Subtotal: 251.1 GL

Applicable Data: 663.36 Gigaliters

4.5.7 System Loss (Cufw)

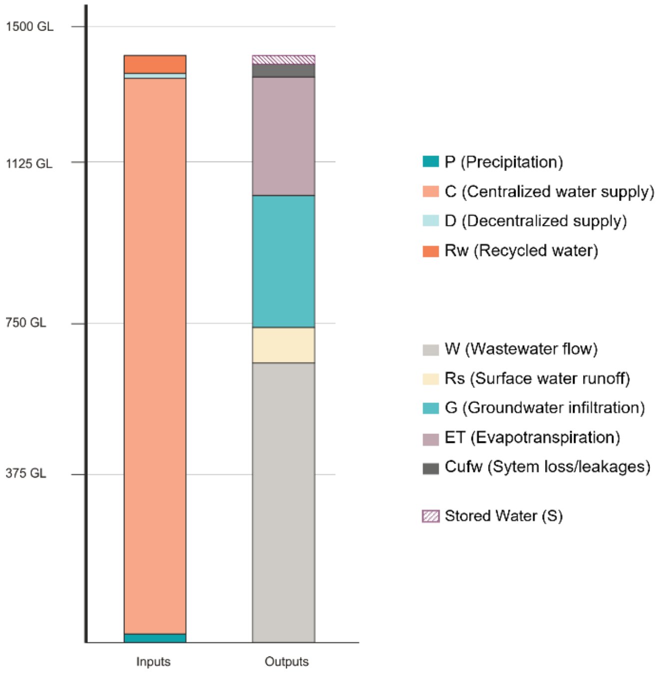
Quality of data: Low

The city of Lima has a deficient infrastructure. Its primary pipeline network is more than 30 years old, and almost 30 kilometers receive insufficient maintenance, and its system for measuring connections to the network is unreliable (MML, 2014, p.773). According to SUNASS in Lima, at least 69 thousand liters of drinking water are lost per second, a problem that SEDAPAL, through its statistical records and under the label of Not Invoiced, confirms (Ziegler and Morales, 2020). Indeed, the state-owned company states that 30% of water is lost annually due to clandestine connections, meters with under-registration, physical losses, among other minor ones. During the 2016 period, water production was 714.7 Mm³, and only 514.7 Mm³ of the total was billed. During 2017, production was 699 Mm³, and 523.3 Mm³ were billed (SEDAPAL, 2016, 2017). The conversion factors showed in the Methodology section (see Chapter 1) were used for the calculation. Then:

System Loss:
Unbilled: 187.85 Mm³ = 187.85 Hm³
Applicable Data: 187.9 Gigaliters

4.5.8 Results INPUTS - OUTPUTS

The collected data were used for the ML urban metabolism analysis using the adapted water mass balance equation described in the Methodology section (see Chapter 1). The results show all inflows and outflows applied to the selected system boundary (Metropolitan Lima), finding a positive change of 13.2 Gigaliters (GL) in the city's stores, as shown in Figure 60. Although this value should be zero according to urban metabolism theory (see Chapter 2), the result may be due to some calculation errors, especially those used to quantify the value of decentralized systems and surface runoff coefficients, which require further study for accuracy



Total INPUTS: 26.49 (P)+1364.6 (C)+4.97 (Dg)+46.98 (Rw) Gigaliters
Total INPUTS: 1,443.04 Gigaliters

Total OUTPUTS: 578.6 (W)+ 116.4(Rs)+ 295.9 (G)+251.1(ET)+187.9 (Cufw) Gigaliters
Total OUTPUTS: 1,429.82 Gigaliters

Figure 60: UWMB Inputs and Outputs in ML

Source: Created by author

Comparing urban settings where metabolic analysis has been applied through the UWMB methodology reveals interesting similarities and differences to be expanded, as shown in Table 10. In rainfall, cities such as Bangalore, with a mountain range embedded along with the city and an uneven landscape with a mix of hills and valleys, presents 78 GL (almost three times more than Lima). In contrast, in environments with topographic relief farther away from urban centers such as the case of Australia, cities such as Melbourne present a total of 1,352 GL (almost 50 times more than Lima), and in the case of Perth (907 GL), 34 times more than the precipitation levels of the case study (Kenway, Gregory and McMahon, 2011; Paul *et al*., 2018; ANA, 2021). These findings reinforce that the city's topography and proximity to such diverse altitudinal levels play an essential role in Lima by behaving as a barrier to warm winds, only achieving significant accumulations of fog and high levels of humidity in the upper parts of the city's slopes. Therefore, the fog merits further study in the future by being a possible water alternative resource still untapped in the geographical region of the Peruvian coast. Indeed, these inherent characteristics of Lima must be contemplated in any water-sensitive strategy; otherwise, the urban metabolism would be altered.

On the other hand, subsequent studies such as Renouf (2018) highlight that non-harvested rainfall should be considered. However, this aspect is not considered in the calculation of Lima. There is a lack of available data, and the studies used as reference (Australia and Bangalore) do not contemplate it either (Renouf *et al.*, 2017).

Another critical finding is concerning centralized and decentralized sources. Lima is a unique case in that even in a similar context, given the condition of developing countries, Bangalore's water system does not rely exclusively on imported water. Its decentralized sources total 312.1 GL (almost 63 times more than Lima) are practically proportional to the centralized ones (356 GL). However, this could be due to a more significant gap in domestic water and sanitation connections in the Indian city than the Peruvian capital and domestic use abstraction wells as an alternative source (Paul *et al.*, 2018). In the case of Australian cities, the situation is very different. All the cities focus their decentralized sources on rainwater collecting tanks (in the range of 1 to 5 GL annually), so the data is not comparable being Lima, a city with low rainfall levels (Kenway, Gregory and McMahon, 2011). Only Cape Town presents similar parameters with a greater dependence on centralized systems than Lima's case.

Regarding wastewater reuse, it can be observed that, in general, the values are still low in Indian cities such as Bangalore and Cape Town. In the case of Oceania cities, and as seen previously in Chapter 3, it is well-known that over the last few years has potentialized this its use as an alternative source for non-potable consumption. Therefore, the data (considering the year in which they were collected) must have undergone favorable variations (Kenway, Gregory and McMahon, 2011; Paul *et al.,* 2018).

Urban System		**Lima**	**B**	**CT**	**P**	**M**
Population (Million inhab)		10.5	9.5	4.0	1.9	4.5
Qi	Centralized Supply (C)	1,364.6	356.3	341.9	229.0	431.0
	Decentralized Supply (D)	4.97	312.1	3.6	196.0	8.0
	Centralized Recycled Water (Rw)	46.9	3.0	29.0	5.0	31.0
	Precipitations (P)	26.5	78.0	1135	907.0	1,387.0
	Total Qi (GL)	1,443.0	748.3	1,509.6	1,337.0	1,857.0
Qo	Wastewater (W)	578.6	362.0	234.2	111.0	346.0
	Surface Runoff (Rs)	116.4	40.0	19.2	200.0	300.0
	Groundwater Recharge (G)	295.9	4.4	65.0	363.0	
	Evapotranspiration (ET)	251.1	33.2	1,050.8	1,000.0	1,251.0
	System Loss (Cufw)	187.9	178.6	72.2		
	Total Qo (GL)	1,429.8	618.3	1,441.4	1,679.0	1,928.0
Stored Water (S)		13.2	130.1	68.2	-342.0	-72.0

Table 10: Comparative metabolic analysis

Source: Created by author

As far as OUTPUTS is concerned, the comparison shows that in the case of Bangalore, there is a predominance to not treating wastewater (171 GL), a value 2.4 times higher than in the case of Lima. Regarding treated wastewater receiving preliminary or primary treatment, Lima produces 2.8 times more than the Indian city. Indeed, this reflects a positive aspect in the Peruvian capital compared to other developing cities, although, as previously mentioned, the challenge today is to increase secondary and tertiary technologies. In the framework of losses in the system, the case of Bangalore shows a value (179 GL) very similar to that found in Lima, reaffirming the wisdom of incorporating this factor in the equation for developing contexts (Paul *et al.*, 2018).

4.5.9 Efficiency Indicators

The application of the indicators reaffirms that in the current scenario in Lima, almost 100% of the total water entering the urban environment comes through a centralized system, as exposed in Table 11. Although 26% of the demand is satisfied by decentralized systems such as dams and lagoons in the upper basin (outside the urban environment), these flows join the natural surface from the Rimac and Chillon rivers before entering the city. Therefore, they are considered centralized due to their level of dependence. The results in the rainfall framework show a low percentage of substitutability (1.94%) due to the minimal volume of precipitation within the selected area.

On the other hand, the total and centralized substitutability is 42% for wastewater water use. This result means that the amount of wastewater (578.6 GL) could substitute 100% of the regulated flows (350.6GL) plus a large percentage (51%) of the surface water coming from the Rimac River (228 GL). The substitution potential of wastewater (578.6 GL) is approximately 22 and 5 times higher than that of rainwater (26.5 GL) and stormwater (116.4 GL), respectively, indicating that Lima is an extremely dry city. The indicators also show that the potential for substituting total use from the recovery of water losses is 14%, meaning that 187.9 GL could be used as inputs in the system.

From this, it is evident that wastewater recycling and improving water efficiency in the water supply network have a great potential to increase water in the Metropolitan Lima system, a situation very similar to the case of Bangalore. Compared to cities such as Perth or Melbourne, the situation differs significantly, as the most significant potential for water substitution is found in the recycling of rainwater due to the high percentage of rainfall. However, the results also show that a single alternative source, in the case of wastewater reuse, does not have sufficient potential to meet the total water demand of Metropolitan Lima. Integrated management of all water sources, including the current centralized system, is essential to address water scarcity.

Thus, by harnessing 100% of the potential of rainwater, stormwater, water loss recovery, and wastewater recycling and reuse, a total of 882.9 GL per year (or 73.5 GL per month or 2.4 GL per day) could be reinserted into the system under a hybrid scheme. However, as will be discussed in Chapter 5, these data must be adapted to scenario development.

Water System Centralization			
Supply Centralization	Centralized Supply/Total Water Use	C/(C+D) *100	99,64%
Rainfall Potencial for Water Supply			
Centralized Supply Replaceability	Rainfall/Centralized Water	P/C*100	1,94%
Total Use Replaceability	Rainfall/Total Use	P/(C+D)*100	1,93%
Wastewater Potential for Water Supply			
Centralized Supply Replaceability	Wastewater Flow/Centralized Water	W/C*100	42,40%
Total Use Replaceability	Wastewater Flow/Total Water Use	W/(C+D)*100	42,24%
Stormwater Potential for Water Supply			
Centralized Supply Replaceability	Stormwater flow/Centralized Water	Rs/C*100	8,53%
Total Use Replaceability	Stormwater flow/ Total Water Use	Rs/(C+D)*100	8,50%
Wastewater and Stormwater Combined			
Potential of Total Water Use Replaceability	(Wastewater+Stormwater)/Total Water Use	(W+Rs)/(C+D)*100	50,74%
Centralized Supply Replaceability	Water Loss/Centralized Water	Cufw/C*100	13,77%
Water Loss Recovery Potential of Total Water	Water Loss/Total Water Use	Cufw/(C+D)*100	13,72%

Table 11: Lima metabolic analysis efficiency indicators

Source: Created by author

Many cities around the world lack reliable information about alternative water resources in their water systems. The UWMB study applied to Lima explores a suitable framework for analyzing the water system in the city, proving to be a helpful tool for identifying which flows have the potential to increase and diversify water sources and answering the research sub-question. However, for a better understanding and relative level, it is required that the methodology be applied to similar environments since there are very few references in terms of urban environments in developing countries (most are utilized in developed contexts). Indeed, Lima is the third known case (in addition to Bangalore and Cape Town). This aspect will be beneficial to adapt the equation further, define existing flows more precisely, and even identify possible additional flows in environments where clandestine connections or leaking pipes play an important role. It is also worth mentioning that, as Hegyi states in his study of Cape Town, although the equation is useful, it simplifies many complex data by translating them into a few variables, both at the level of the equation and the indicators making use of rounding and assumptions. In that sense, the UWMB should be understood as an estimation-based assessment framework. If included as a basis for developing a water-sensitive strategy, it should be supported by a spatial level analysis of the inherent characteristics of the selected urban environment and even a governance analysis, as is the case in the research (Paul *et al*., 2018; Hegyi, 2019).

4.5.10 Water Demand

Another aspect, which, although not part of the metabolic analysis of the water cycle in Lima, is the analysis of water demand, allowing a better understanding of how water resources are distributed within the city.

The ANA grants the concessions of water use rights over natural sources for different uses, among which, according to the Water Law, population use has priority over other sectors. Each user must declare the annual volumes to pay the economic retribution for the right of use, differentiating between consumptive use (with consumption) and non-consumptive use. The latter implies that the water used is subsequently returned to the source from which it was extracted, although not to the same place. During the periods 2016-2017, the total volume allocation for all uses amounted to 4,255 Hm³, of which 1,144 Hm³ are for consumptive use and 3,111 Hm³ for non-consumptive use. It should be mentioned that the value of consumptive use only contemplates those users with a formally registered connection. In other words, it does not cover the population that does not have the service, which, as previously mentioned, amounts to 14% of the inhabitants in Lima.

The demand for water for consumptive use in Lima is mainly for population use, accounting for 69% of the total, followed by agriculture (22%), industry (8%). In comparison, recreational and mining represent the lowest demand in the 1% range, as indicated in Figure 61. In mining activities, the granting of rights is in the middle basin outside the city limits. In the case of demand for energy use, water is used for energy production. It is then returned mainly to the Rimac River (98.8%) and a lesser extent, to the Chillon (1.2%), so it is considered non-consumptive use. Nevertheless, it is not clear if it is returned with physicochemical or even biological alterations. In terms of spatial distribution, agricultural demand is predominantly concentrated in the Lurin basin due to the concentration of agricultural land in the area (ANA and GIZ, 2018, pp. 41-46; OA CHIRILU and GIZ, 2019, pp. 64 -69; Ascencios *et al.,* 2019).

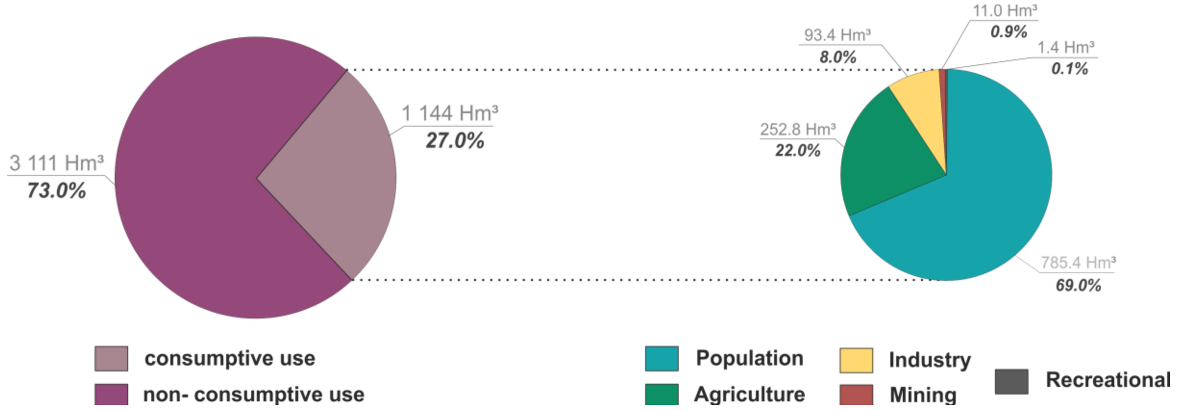


Figure 61: Consumptive water demand in ML

Source: Created by author, adapted from ANA and GIZ, 2018; OA CHIRILU and GIZ, 2019.

Regarding the demand for population use, the right of use is granted to SEDAPAL, 75% of the supply is covered by surface sources (natural and regulated) with a significant predominance of the Rimac River basin over the others (Chillon and Lurin) and 25% by groundwater sources through wells, as shown in the metabolic analysis. In the latter case (groundwater sources), districts like Carabayllo, Callao, San Juan de Lurigancho, and Ate are mainly supplied from the aquifer and not from surface sources. Over the last few years, demand has increased by 11% compared to 2013 (706.9 hm³), mainly due to population growth and per capita water demand and a weak water culture among the population and various factors previously analyzed in the section Living in the desert of the chapter.

The demand for industrial use (93.4 hm³) also presents an increase of three times its value compared to 2013 (29.6 hm³), a request that is also 87% covered by groundwater and with a more significant predominance of the Rimac basin, as shown in Figure 62. Agricultural uses are satisfied through surface water, covering 92% of the demand; in the Lurin basin, this uses more groundwater than other valleys. In the case of the coverage of the need for irrigation of green areas, the supply comes from multiple sources: 39% use irrigation canals (supplied by the Rimac River), 27%, drinking water from SEDAPAL, 17%, groundwater, 13%, tanker trucks, and 4%, treated wastewater, where districts such as Miraflores, Punta Hermosa and Villa el Salvador stand out. In contrast, the districts of Cercado de Lima, La Molina, San Juan de Lurigancho, San Miguel and Santiago de Surco are those that used the greatest volume of potable water and San Borja, San Isidro, Santiago de Surco, Ate and El Agustino are those with the greatest demand.

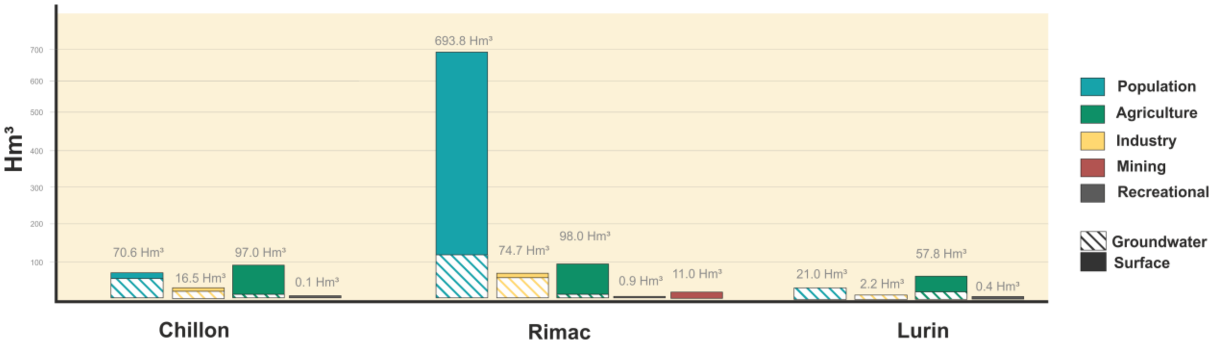


Figure 62: Water demand covert by Rimac, Chillon, and Lurin rivers

Source: Created by author, adapted from ANA and GIZ, 2018; OA CHIRILU and GIZ, 2019.

Regarding the demand for irrigation of public green areas, the type of cover required for irrigation plays an important role and dramatically impacts the water demand. Plants have different water requirements; while some consume large amounts of water, others can survive with low amounts of water. A study conducted in Lima shows that American grass (*Stenotaphrum secundatum*) has the highest annual water demand of 1052 liters per square meter instead of the water required by xerophytic shrubs (*aptenia cardifolia*), whose demand does not exceed 316 liters per square meter. American grass is planted in 80% of urban green areas (Eisenberg *et al*., 2013, pp.155-163). The predominance responds to a lack of knowledge about the suitability of species in desertic contexts and the association of greenery as an aesthetic element. This factor, as well as the irrigation system, are aspects that will have to be taken into account when developing a water-sensitive strategy (ANA and GIZ, 2018, pp.41-46; OA CHIRILU and GIZ, 2019, pp.64-69; Ascencios *et al.,* 2019).

As analyzed in the Urban Metabolism section above, the flow of water entering Lima is 1,364.6 Hm³ (Centralized Supply (C)) from natural and regulated surface sources, as well as groundwater. However, according to ANA, only 1,176 Hm³ of the total water entering the city is collected and potabilized. The remaining volume of water (188.6 Hm³), which is usually available during flood periods, cannot be collected because it exceeds the collection capacity of the existing infrastructure (ANA and GIZ, 2018, p.49).

This situation implies that although the necessary demand for consumptive uses is covered (1,144 Hm³), there is only a surplus of 32 Hm³. However, it should be considered that the flows of the rivers that supply the city are irregular, and in order to cover the demand, regulated sources are used. Thus, Lima faces water crises during periods of drought. As shown in Figure 63, facing a 40% increase in population and demand, as stipulated in the studies (457.6 Hm³ more), the volume would not be sufficient, resulting in a physical deficit of approximately 425 Hm³ by 2035 concerning the volumes captured by SEDAPAL (Stakeholders, 2020). Moreover, as mentioned in the first section of this chapter, a large percentage of the population faces economic water scarcity due to the lack of water and sanitation services. This scenario confirms the need to diversify sources, as stated in the UWMB results in Lima.

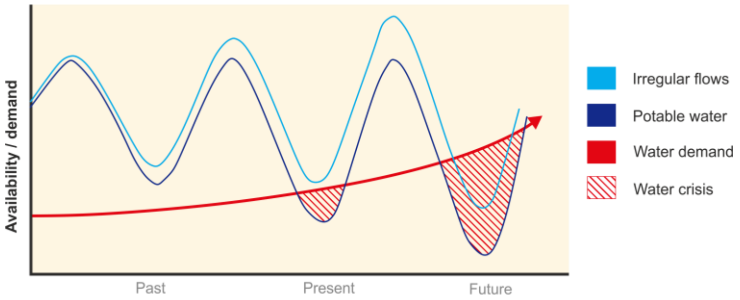


Figure 63: Water deficit by 2035

Source: Created by author, adapted from AQUAFONDO, 2016.

4.5.11 Water Quality

An essential aspect of analyzing is water quality, as this factor could significantly condition the potential of the sources in the face of hybrid management. Lima does not have a comprehensive and permanent system for monitoring and evaluating water quality; in this sense, the monitoring of physicochemical and biological aspects is carried out for independent purposes by various public institutions such as DIGESA, SEDAPAL, or ANA, as well as by private entities. However, in 2008, the Environmental Quality Standards (ECA) were approved through the Ministry of Environment - Supreme Decree N°002-2008- MINAM. In essence, it is the measure that establishes the level of concentration or degree of elements, substances or physical, chemical, and biological parameters present in the air, water, or soil, in its condition of receiving body, which does not represent a significant risk to the health of people or the environment. When the effluent from a WWTP is discharged into the receiving water body, a mixing zone is created, after which the receiving water body must comply with the ECA-Water values, which depend on the category of use of the receiving body: Category 1 - (A) human consumption, (B) recreational, Category 2 - (C) extraction, cultivation and other marine and coastal activities, Category 3 - (D) irrigation of vegetables and drinking water for animals, and Category 4 - (E) conservation of the water environment. In order to strengthen these regulations, in 2010, Supreme Decree N°003-2010- MINAM approved the Maximum Permissible Limits (MPL) for effluents. The objective was to control excess concentration levels of physical, chemical, and biological substances present in effluents or emissions (i.e., before contact with the receiving body) to prevent damage to health and the environment (Loose, 2015, p. 24).

In general, the deterioration in water quality of the water resources that supply Lima is caused by anthropic pollutants that alter the natural physicochemical and bacteriological characteristics of rivers and, consequently, the city's marine coastline. According to the inventory of pollutant sources, untreated wastewater discharges (domestic, industrial, municipal, agro-industrial, among others), pipes connected to the riverbed as a result of direct discharges from the population settled in the marginal strips, solid domestic, industrial, and construction waste dumps, mining liabilities and indirect pollutant sources have been identified. It should also be noted that the Rimac watershed has the highest concentration of contaminating sources along its course, as shown in Figure 64 and Table 12. This situation is mainly because of pipes directly connected to the riverbed (302), the presence of 221 solid waste points, 172 residential water discharges, and, as mentioned in the previous section, more than 27 contaminating points from mining activities (OA CHIRILU and GIZ, 2019, p.43).

Pollutant Source		**Chillon**	**Rimac**	**Lurin**
Wastewater discharges		25	172	8
Irrigation water discharges		-	-	3
Pipelines with direct connection to a watercourse		7	302	-
WWTP effluent		1	221	4
Solid waste landfill	Residential	34		20
	Construction	5		4
	Organic waste	-		5
Indirect pollutant sources		16	5	23
Mining liabilities		-	27	-
Total		**88**	**727**	**67**

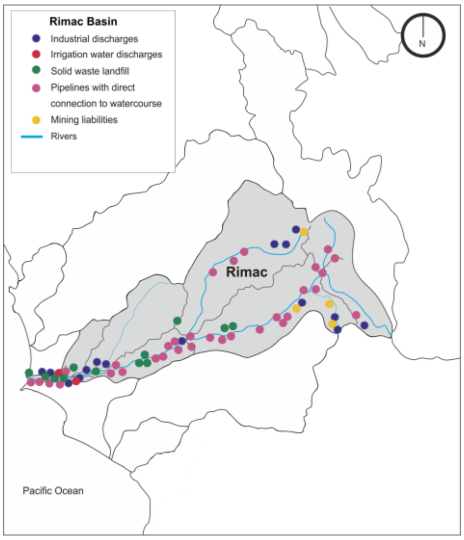


Table 12: Pollution in CHIRILU rivers

Figure 64: Rimac basin polluted areas

Source: Created by author, adapted from ANA and GIZ, 2018; OA CHIRILU and GIZ, 2019.

To calculate the water quality index, the ICA-PE is used, a methodology approved by the ANA that establishes five ranges in water quality status: Very poor (where water quality does not meet quality objectives and is almost always threatened or deteriorated), Poor, Fair, Good and Excellent (where water quality is protected with no threats or damage). In addition, parameters related to organic load levels (thermotolerant coliforms, pH, dissolved oxygen, biochemical oxygen demand, chemical oxygen demand, nitrites, nitrates, and other dissolved salts) are monitored, as well as parameters associated with the presence of metals such as aluminum, cadmium, arsenic, and iron.

In the case of the Rimac River, the results show that the lower basin area and the Huaycoloro stream are the most affected by domestic and industrial wastewater discharges, with biological oxygen demand (BOD), chemical demand for oxygen (CDO), and coliform tolerant values exceeding the ECA standards. In the upper watershed, outside the city limits, and as previously mentioned, its waters contain lead, cadmium, and arsenic in quantities more significant than the ECA, and these values, although lower, persist in the lower part of the watershed where Lima is located. In the Huaycoloro stream, classified as Poor, the levels of thermotolerant coliforms, iron, phosphorus, and arsenic are very high, as shown in Figure 65. On the Chillon River, the study indicates in the lower zone, parameters of thermotolerant coliforms, aluminum, and iron above the ECA (Category 3), contrary to those shown in the upper area, which is below the Environmental Quality Standard for Water (Cat.1-A2), except for fecal coliforms and iron, which are above the ECA. In the lower part of the Lurin River, water quality is Poor due to the high presence of thermotolerant coliforms; however, water quality is excellent in the upper part of the river (MML, 2014, pp.186-191; ANA and GIZ, 2018, p.33; OA CHIRILU and GIZ, 2019, pp.43-45).

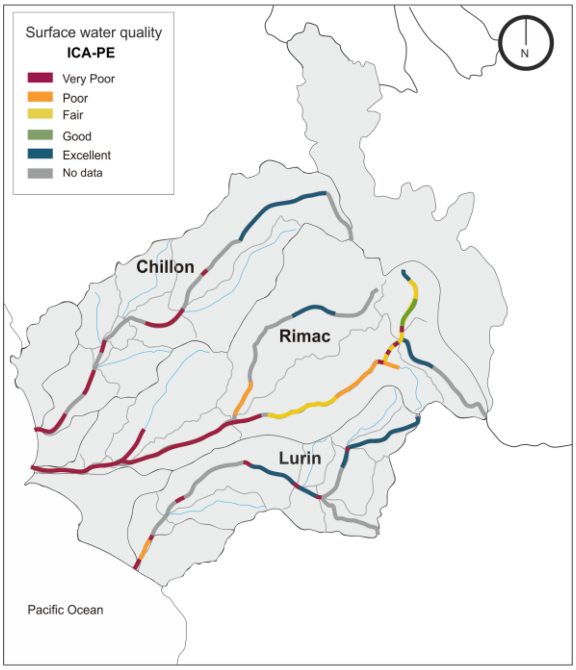


Figure 65: Surface water quality

Source: Created by author, adapted from ANA and GIZ, 2018; OA CHIRILU and GIZ, 2019.

Regarding groundwater quality and taking as a reference the measurements taken in the 2016-2017 period by covering the most extensive number of wells monitored (302), three aspects should be highlighted. The results generally show a quality within normal to excellent ranges, especially in the Rimac and Lurin aquifers. Nevertheless, they present isolated points of a lower rate that merit constant monitoring. A different situation is shown in the Chillon aquifer, with quality within regular to very poor ranges, as indicated in Figure 66. Another aspect to highlight from the results is a trend towards the deterioration of groundwater quality. Between 2014 to 2017, there was a reduction of 11.3% in average to excellent ranges of the wells.

The parameters used in the measurement conducted with SEDAPAL were electrical conductivity (EC), turbidity (UNT), hydrogen potential (pH), chloride (Cl-), sulfates (SO42-), hardness (CaCO3), and nitrates (NO3-). Although the values obtained for each parameter compared with the Maximum Permissible Limits (MPL) for water quality for human consumption conclude "Desirable States," it is necessary to highlight the exceedance of the parameters at some points along the rivers. This situation is due to the chemical decomposition of the calcareous and sulfate rocks that dominate the city area. It releases chemical compounds such as SO42+ or CaCO3, increasing the total solids in the water and, therefore, the electrical conductivity. On the other hand, the high nitrate values are presumably due to agricultural activity, the absence of monitoring of fertilizer use, and even livestock excrement. The truth is that the assessment still lacks data on the use of hydrocarbon pesticides, BTEX, or heavy metals and more frequent data collection, reducing the effectiveness and efficiency of the studies (ANA and GIZ, 2018, p.34; OA CHIRILU and GIZ, 2019, p.46).

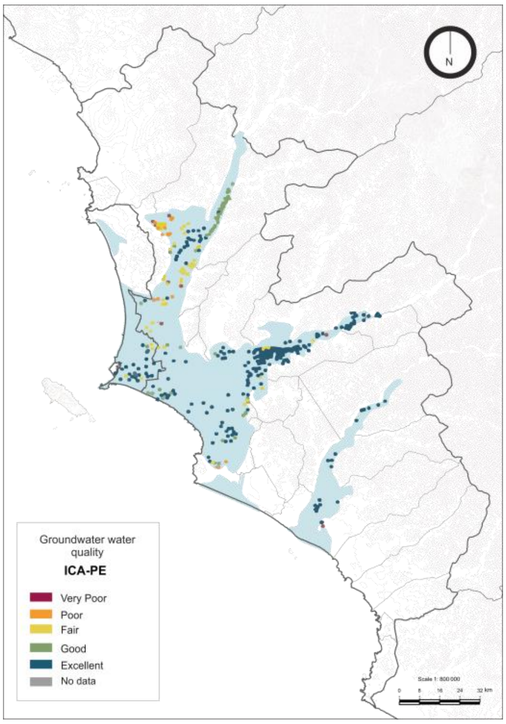


Figure 66: Groundwater quality

Source: Created by author, adapted from ANA and GIZ, 2018; OA CHIRILU and GIZ, 2019.

Another critical aspect of the quality standards is marine pollution, especially considering the three rivers that supply the city flows into the bay. According to the analysis carried out by the General Directorate of Environmental Health (DIGESA), 31 untreated discharges into the sea have been identified, especially with high concentrations of thermotolerant coliforms, including the Chillon, Rimac, and Lurin rivers and the WWTP La Chira collector. The assessment highlights the severe contamination levels in the Callao Bay (Ventanilla district), reaching oversaturation levels (MML, 2014, pp.191-193).

Given the high percentage of the population that still does not have connections to the water and sanitation network, as previously explained, tanker trucks fill the infrastructure gap and supply the inhabitants with a source of daily consumption. However, they are not regulated in terms of tariffs, much less in terms of quality standards. According to research conducted by Ziegler and Morales (2020), water has a significant presence of bacteria associated with the intestinal tract of animals and even humans. It can cause various stomach problems such as vomiting, diarrhea, and even severe infections if consumed. In addition to identifying other organisms (algae and protozoa), the results showed the presence of lead in values well above the limits established by Peruvian regulations. Furthermore, it confirmed the low levels of chlorination through which the water passes by having chlorine levels well below drinking water standards (Ziegler and Morales, 2020).

4.6 Natural Hazards and Climate Change Risks

Metropolitan Lima is constantly exposed to multiple natural hazards that can affect humans, activities, or infrastructure. Several natural factors are associated with these hazards, such as the city's location, soil type, and particular topography (slopes). In some cases, for anthropogenic reasons, such as the occupation of vulnerable land or inadequate construction practices (poor quality materials), the risk is even greater. The danger that would cause the most damage is related to seismic activity due to the city's proximity to the zone of interaction of the Nazca and South American tectonic plates. The danger of tsunamis, rock falls, soil liquefaction, dry flows, among others, is also associated with earthquakes.

Lima has endured many earthquakes of great magnitude and tsunamis throughout its history; the most important occurred in 1586, 1609, 1655, 1687, 1746, 1940, 1966, and 1974. These caused panic among the population and a high degree of destruction of housing and infrastructure, especially in areas where geological conditions are less favorable (slope areas) and where the population has less purchasing power and lives in conditions of poverty. According to seismic zoning, Lima is classified into five zones with varying levels of danger.

Zone I (low hazard) is a zone made up of alluvial gravel and rocky substrate. It constitutes most of the city of Lima and is characterized by rigid soil. Zone II (medium hazard) is a moderately stiff zone with clayey or sandy-loamy soil, where amplifications or moderate surface landslides are expected in low and intermediate periods. Zone III (high hazard) are deposits of fine soils and sands of great thickness. They occur in some sectors of the districts of Puente Piedra, La Molina, and Lurin and in the eolian sand deposits that cover part of the districts of Ventanilla and Villa El Salvador. Then there is Zone IV (very high hazard), which are specific areas of eolian deposits such as those observed in Villa El Salvador and the Pachacamac quarries. This zone includes hillside areas and corresponds to material susceptible to soil liquefaction and landslides.

Furthermore, there is Zone V (punctual zones), as shown in Figure 67. This area refers to fills of heterogeneous cuttings that have been placed in natural depressions or excavations carried out in the past. This zone also includes sanitary landfills that in the past were located outside the urban area and have now been urbanized, as is the case in the districts of Rimac, Surquillo, Bellavista, La Perla, San Juan de Miraflores, and San Juan de Lurigancho (Villacorta *et al.*, 2015).

Regarding the areas vulnerable to tsunamis, all of them are located on the coastline or continental shore. These include entire districts such as La Punta and specific regions such as Ventanilla and Chorrillos. Nevertheless, other natural processes expose the city, such as mass movements and floods and, less frequently, sandstorms and erosion processes. Although these processes are not very common and cause minor damage than seismic activity, they still represent a danger if they are not considered in disaster prevention actions.

The most frequent mass movements are rockfalls, landslides, flows (huaycos), and subsidence. In the case of rock falls, the most vulnerable districts are those with moderate and steep slopes such as Comas, Independencia, San Juan de Lurigancho, San Juan de Miraflores and Villa María del Triunfo. In the case of landslides, the Costa Verde area (cliffs) is the most exposed. Huaycos (or flows) are the movement of rocky material or soil in the form of a fluid. Usually, the areas of ravines such as Huaycoloro and Media Luna in San Juan de Lurigancho; the Huaycán, Quirio, Pedregal, and La Cantuta ravines in Chosica, and the Progreso and Collique ravines in Comas, among others, are the most susceptible. The riverbanks are prone to erosion due to informal settlements along the boundaries, especially during El Niño floods. Similarly, in the coastal edge, corrosion is produced by the erosive action of waves and marine currents, leading to the formation of cliffs. There is a high risk of sanding in dune areas such as Villa El Salvador and Ventanilla (Villacorta *et al.*, 2015).

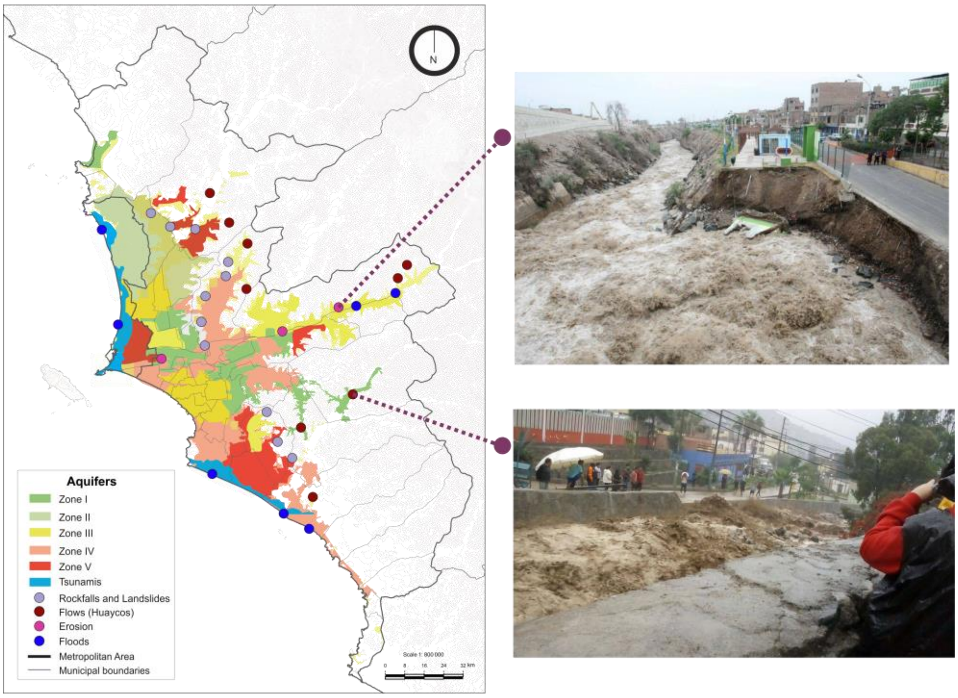


Figure 67: Vulnerable areas to natural disasters in ML

Source: Created by author, adapted from Villacorta *et al.*, 2015; ANDINA, 2017; RPP, 2017

4.6.1 Climate Change

The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) stressed in 2007 that climate change is an undeniable fact and that anthropogenic activities have increased mainly its severity by generating more and more Greenhouse Gases (GHG). The consequences of climate change are evident to a greater or lesser extent in all world regions. Today, changes in temperatures, changes in rainfall amounts, sea salinity, wind patterns show more periods of droughts, heavy rains, or heatwaves, among many others (Zhang, 2007).

Peru is in the 42nd position in the list of countries vulnerable to climate change, with Lima being one of the cities most exposed to suffer the impact. According to the Metropolitan Municipality of Lima (MML) in its latest Climate Risk Analysis (ARC), it is estimated that the meteorological variables of precipitation and temperature will intensify progressively in the coming years based on a scenario of high GHG emissions (MML, 2021). In 2009, the projection for 2030 was for an increase in maximum temperature of up to 1.6°C on average and, in the case of precipitation, an increase of 20% in the rainy season, as indicated in Figure 68. In contrast, it also shows a decrease of -20% in the dry season (SENAMHI, 2009). Nevertheless, in the 2016 data update, the increases for 2036 are even more significant, up to 2 °C in maximum temperatures and 1.5 °C in minimum temperatures, as well as +/-30% in the case of precipitation, which would increase the desert character of the city and reduce the irrigation capacity of green areas during the winter, which could be gradually lost (MINAM, 2016). This situation will generate more frequent heatwaves, floods, mass movements, and drought, causing potential impacts on Lima's population, economic activities, infrastructure, and ecological balance.

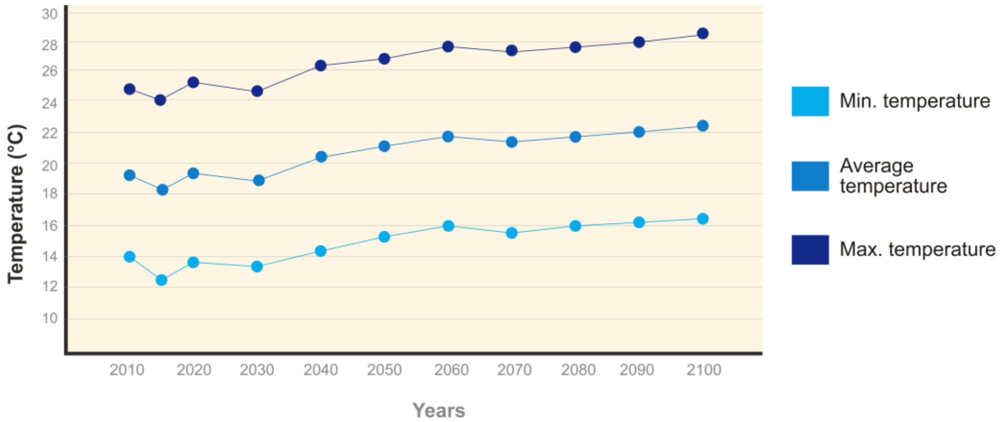


Figure 68: Temperature increase in ML

Source: Created by author, adapted from MML, 2021.

On the other hand, due to global warming, water availability in the headwaters has been seriously affected by the melting of tropical Andean glaciers (TAG). As shown in Figure 69, during the last 30 years, there has been a 43% retreat of the glacier surface, generating short and medium-term problems of droughts and floods for Lima and the areas annexed to the CHIRILU basin, given their dependence on surface water sources (Torres and Gomez, 2008; ANA, 2014).

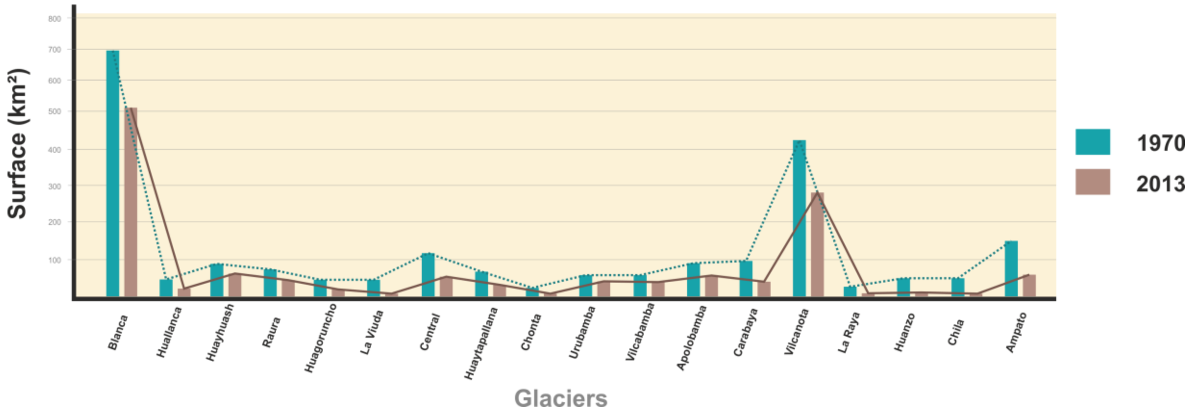


Figure 69: Melting of the TAG during the last 30 years

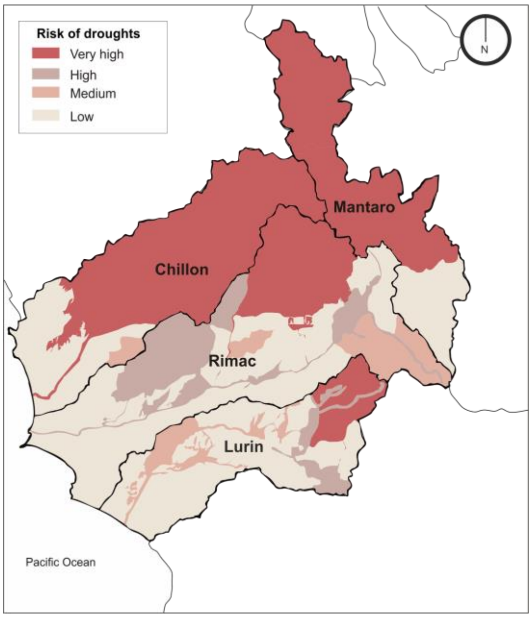
Source: Created by author, adapted from ANA, 2014.

In flooding, the lower basin with the most significant impact would be the Rimac river, with an 11% higher probability in districts such as San Juan de Lurigancho, Chaclacayo, and Ate due to the location of informal settlements on the riverbanks. In the lower Chillon river basin, the districts of Puente Piedra, Comas, and Los Olivos are more vulnerable. While the lower Lurin river basin is at lower risk, the districts of Cieneguilla and Lurin should be noted (SENAMHI, 2016; MML, 2021). Another aspect that stands out in the face of increased rainfall is the morphology of housing in Lima. Almost all of them have flat roofs that require adaptation to avoid flooding, as has occurred in the past (ANDINA, 2009).

As Figure 70 shows, in the case of droughts, they acquire the category of Very High Danger in the upper basin of the Rimac and Chillon, particularly in the area where Lima's main reservoir and water transfer infrastructures are located. With 14.4% more vulnerability, the lower Chillon river basin is more prone to extreme droughts, followed by the Rimac river basin. Prolonged drought seasons would limit the capacity to use groundwater for human consumption, irrigation, commerce, and industry due to lower availability of aquifer recharge, significantly reducing groundwater reserves. In the case of the infrastructure for drinking and wastewater treatment, vulnerability is also high. During droughts, there is a more increased need for treatment due to the lower dilution of effluents. Changes in the water cycle would also significantly impact the city's energy supply, given the high dependence on water to operate hydroelectric plants in the upper basin. The impact of climate change cannot be ignored and requires resilient strategies for the city. Compared to other Latin American cities, Lima is not prepared for droughts and has one of the lowest water reserve ratios in the region (OECD, 2021b). The city only has reserves of 350 Hm³ located in the upper area of the basin. Usually, they are used to regulate the flows of the Rimac River and are also exposed to changes in precipitation levels and deglaciation in the Andean zone of the country. This aspect reduces the city's resilience.

Figure 70: Drought risk along the CHIRILU basin

Source: Created by author, adapted from ANA and GIZ, 2018; OA CHIRILU and GIZ, 2019.



4.7 Water Challenges in Lima

The results reveal that considering the parameters of the Falkenmark indicator, Lima is facing a situation of water scarcity, with a value of 125 m³ per capita, four times less than the absolute scarcity index. A deeper introspection reveals that although today quantitatively the demand for water in the city is scarcely covered, in the future, the context of water scarcity will be greater, not being able to guarantee the security of the resource with local as well as national impacts. Additionally, the results show that a large percentage of the population also faces economic water scarcity, reducing their quality of life. The development of this section is an attempt, after analyzing the inherent characteristics of the ecological infrastructure, the governance system, and the urban metabolism of Lima, to understand the factors and linkages that aggravate the situation of water scarcity in the city. Thus, the section seeks to answer the question, What are the main socio, ecological and spatial drivers of Metropolitan Lima's water scarcity and water insecurity?

Metropolitan Lima's water supply is concentrated in 75% of surface sources (regulated and natural), coming mainly from the Rimac river of the irregular regime and to a lesser extent from the Chillon and Lurin rivers. According to the granting of rights for water use, the population has priority by receiving 69% of water availability. Nevertheless, the demand has increased by 11% during the last few years due to rapid population growth, weak water culture, and the overuse of drinking water for irrigation systems of green areas that are neither efficient nor sustainable. Only in 2016, the allocation of volumes for consumptive use reached 1,144 Hm^3 implying a daily per capita consumption of 254 liters, well above the 100 liters recommended by WHO, being among the highest in the region and with a heterogeneous character. Lima's central areas consume up to 477 liters, while in peri-urban areas with lower purchasing power, it is between 16 and 41 liters per person per day. Today in Lima, with 10.5 million inhabitants, the available water resources are minimally sufficient to cover the population, agricultural, industrial, and energy demands since the supply captured by SEDAPAL is 1,176 Hm^3 while the demand for consumptive uses is 1,144 Hm^3. Projections stipulate that by 2035 the population will grow at an annual rate of 1.5%, increasing the population's demand for water by 40%, representing a challenge for water resource management.

From the technical point of view, water resources management in Lima represents a unique case compared to other case studies of similar characteristics since it is dependent on centralized systems. This factor symbolizes a high degree of vulnerability in the availability of resources in the face of estimated variations in temperature and precipitation due to climate change, producing more frequent scenarios of heatwaves, floods, mass movements, and drought, and impacting the population, its economic activities, infrastructure, and the ecological environment of the city.

Faced with this challenge, although wastewater recycling and improving water efficiency in the water supply network have a potential of 42% to increase water in the ML system, it does not have sufficient potential to meet the total water demand, requiring its complementarity with hybrid systems. The government is innovating to develop desalination plants, but these still treat minimal volumes and represent high operating costs compared to other decentralized schemes. In addition, in the upper zones of the CHIRILU basin, Lima's reservoir and diversion infrastructure regulate the rivers' variable flows by providing 350.6 GL. Nevertheless, deglaciation in the Andean zone reduces water availability, decreasing the city's resilience capacity as it does not have the necessary reserve ratios per capita to cope with prolonged drought seasons. Metabolic analysis of the natural and artificial water sources that converge in the city shows meaningful findings even though it simplifies highly complex data and is based on assumptions. While there have been significant advances in wastewater treatment, primary technologies, lack of maintenance in the WWTP, and disconnection with pre-Hispanic irrigation canals significantly reduce the potential for use as an alternative source for potable and non-potable consumption. Lack of maintenance in the city's primary water and sewage network results in the loss of a third of the current supply due to leaks, a common factor in developing environments.

Problems with water quantity are aggravated by threats to water quality, a factor that could also significantly condition the potential of the sources in the face of hybrid management. The Rimac basin has the highest concentration of pollutant sources along its course in the lower basin with more than 300 pipes directly connected to the river, 221 solid waste points, and 172 residential water discharges with very high BOD, CDO, and coliform tolerant values. In the middle basins, outside the city limits, more than 27 contaminating points from mining activities have also been located, resulting in high levels of metals such as arsenic, cadmium, iron, and lead in quantities more elevated than the ECA, which persist in the watersheds. The Chillon River also shows high levels of thermotolerant coliforms, aluminum, and iron. At the same time, the Lurin River has an increased presence of thermotolerant coliforms, presumably due to the dumping of solid waste, as opposed to the upper part of the basin, where water quality is excellent. Nevertheless, the deterioration of surface water quality also affects the marine coast in the entrance areas, reducing the oceanic ecosystem balance. Groundwater quality is mainly in the normal to excellent range.

One of the main problems affecting the health of the rivers that supply water to the city is informal human settlements along the riverbanks, which contribute heavily to pollution levels, increased illegal extraction, and depletion of aquifers, making it difficult for the riverside ecosystems to recover. Lima's growth, based on the demographic explosion, has engendered formal and informal urban expansion processes. The city has a heterogeneous distribution at the territorial level and is stratified from an urban, economic and social development perspective. The population located in the central and consolidated areas has greater access to essential services and equipment, transportation, and higher quality of life standards.

On the other hand, the peri-urban areas are home to a population with fewer resources and limited access to basic needs such as water and sanitation services, even though access to these services is a constitutional right. The disparity of access to water faced by more than 1.5 million inhabitants in Lima is also measured in monetary costs, paying up to 10 times more than a formal user and with sanitary conditions far below minimum standards. Informal areas in the city, both in riverside and the peri-urban regions on hillsides, are at greater risk from natural hazards (floods, landslides, erosion) and seismic movements due to the geomorphological conditions of the terrain they inhabit. Furthermore, in peri-urban areas with a higher population density, there is a very high deficit of public spaces instead of the nine square meters per inhabitant that a small group of inhabitants enjoys in the city's central areas. In access to green zones, although the equivalent index is 3.06 m^2/inhabitant in the city, which is very low compared to the recommended level, access is almost nonexistent in peri-urban areas.

ML has a dynamic landscape characterized by natural and anthropogenic elements that have adapted to bioclimatic, geomorphological, and ecological conditions that, although not indispensable, are under constant pressure. Gone are the pre-Hispanic periods of water harmony with the environment, incorporating a network of irrigation canals for cultivation areas and dams to collect water and recharge the aquifer to protect the ecosystemic balance. Today, on the contrary, the city's ecological infrastructure, made up of blue and green elements, is facing formal and informal processes of urban expansion and land-use change that, if left unattended, could have dysfunctional effects on the already worn-out urban water cycle.

The coastal hills, a vital landscape element and natural habitat for many endemic species, reduce their limits and dimensions annually. The same scenario happens with the agricultural areas of the city, losing 90% of the original surface and putting at risk the stability of the aquifers whose recharge is diminished by the progressive disappearance of the agricultural valleys and the sealing of the soil surface due to urbanization. Wetlands, essential biodiversity hotspots, and vital elements for regulating water in river basins and purifying pollutants face constant reductions in their areas of influence. The loss of ecological infrastructure, in addition to its value in the urban water cycle, reduces the capacity to protect against floods and erosion on hillsides and streams, increasing the population's vulnerability.

However, the greatest challenge facing water in Metropolitan Lima is related to the governance system at the national level, at the basin scale, and, although to a lesser extent, also at the city scale. Although there is a consolidated regulatory framework with multisectoral characteristics following the approval of the Water Resources Law and the choice of Integrated Water Resources Management (IWRM) as the central axis, implementation in practice is limited by institutional, territorial, and hydrological planning, participation, and financing factors. At the institutional level, there is a lack of consistency between the objectives pursued at the ministerial level, finding that neither water nor climate change is the guiding thread as would be expected.

On the other hand, the National Water Authority (ANA) has a weak performance. Although on paper it is the main governing body in the integrated management of water resources at the national level, in practice, being an agency dependent on the Ministry of Agrarian Development and Irrigation, it loses the capacity for execution, and even its impartiality is subject to questioning. At the basin level, although there have been promising advances with the creation of the CHIRILU Basin Council, its representativeness is still weak. It faces a deep institutional fragmentation of the multiple stakeholders, which is primarily based on the absence of an integrated and shared vision, the lack of operational management instruments, the existence of scattered primary information on water resources, the institutional monopoly as well, as a high conflict of interest for the use of water throughout the basin. In addition, there is a lack of balanced participation of civil society stakeholders and municipalities in the upper basins.

The interrelation between land use planning and water management is another critical aspect that reduces the capacity for action. Although on paper, with the approval of the Water Resources Law and its vision by basin, this coherent approach is complied with, in reality, it is not implemented. Throughout the CHIRILU basin, there is a significant mismatch between the delimitation of administrative boundaries (regions, municipalities) and hydrological units, which deepens social and environmental conflicts due to the lack of clarity about the roles and responsibilities of regional and municipal governments. This aspect also affects economic harmony as it encourages duplication of expenditures by the different stakeholders in the basin. Although there are isolated efforts to generate land-use planning instruments with a watershed approach at the regional or municipal level, it is still not given due importance from an integrated perspective throughout the entire CHIRILU watershed. What is certain is that the grouping of the various factors today limits the city's capacity to respond to water scarcity and, if not resolved, could even lead to an extreme situation in the future.

Indeed, the challenges faced by the city to meet water demand are diverse and varied. However, there is a cause-effect relationship of factors that aggravate the water scarcity scenario causing imbalances in the city's ecological system, deepening inequality gaps and social problems, and increasing vulnerability to natural disasters. These factors, mostly anthropogenic, exert even greater pressure on available freshwater and drive the decrease in its quantity and quality in Lima: rapid population growth, the impacts of climate change, weak governance, and inequity in access to services. In the case of natural factors, the desertic condition of the city's environment generates a scenario of natural water scarcity. However, it is aggravated by poor understanding and adaptation. All of these are highly interrelated, as shown in Figures 71 and 72, and represent the baseline scenario on which the Vision is based in Chapter 5.

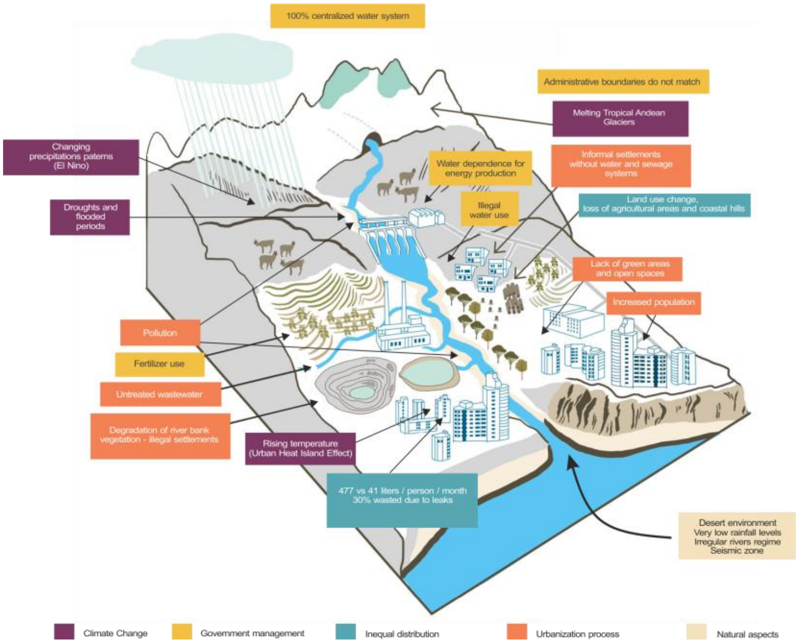


Figure 71: Water challenges in ML

Source: Created by author, adapted from MARIALIBERT, 2021.

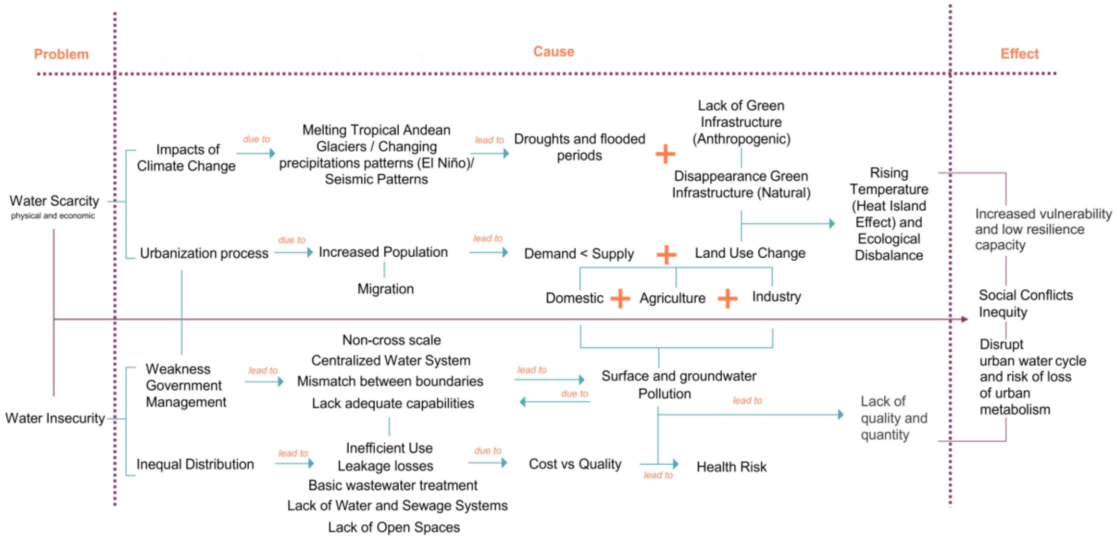


Figure 72: Cause-effect water challenges in ML

Source: Created by author, 2021

4.8 SWOT Analysis

To further summarize the positive and negative aspects of Metropolitan Lima, a SWOT analysis was created and can be found in Table 13 and Table 14. In addition, Figures 73 and 74 contextualize the findings on a map of the city. The SWOT provides an overview of strengths that could be reinforced, opportunities that could be exploited, as well as inherent weaknesses that should be worked on and improved, and threats that should be addressed and mitigated. On this basis, recommendations for improvement can be proposed to increase the city's water sustainability, an aspect that will be discussed in Chapter 5.

For a better understanding and given the complexity of the findings, the results have been grouped into four different categories: Climate Change and Natural Disasters, 2. Water Resources and Infrastructure, 3. Settlement and infrastructure planning, and 4. Governance and participation.

4.8.1 Weaknesses and Threats for Lima – Baseline Scenario (Benchmark)

1. Climate Change and Natural Disasters	1.1 Heat Island Effect / 1.2 Seismic Zone / 1.3 Rising sea level / 1.4 Landslides/ 1.5 Melting of TAG/ 1.6 Increased periodicity and intensity El Niño/ 1.7 Floods in areas near rivers/ 1.8 Droughts/ 1.9 Lack of an early warning system for extraordinary events.
2. Water Resources and Infrastructure	2.1 Limited drinking water Supply/ 2.2 Water scarcity as an environmental condition: No precipitation in a desertic environment/ 2.3 Pollution of rivers and canals / 2.4 Loss of water due to leaking pipes and illegal connections/ 2.5 100% centralized system / 2.6 Variable flows throughout the year/ 2.7 Only 7% of wastewater is recycled / 2.8 Water dependence for electricity generation/ 2.9 Lack of maintenance of water infrastructure in the upper part of the basin / 2.10 Only 2.1% of the country's water resources supply the coast, which is home to 65% of the national population.
3. Settlements and infrastructure planning	3.1 Lomas, wetlands and endemic species at risk/ 3.2 Increased population and density / 3.3 Pressure and reduction of agricultural areas/ 3.4 Inequality in the distributions of drinking water / 3.5 Population in informal areas without connection to water and sewage systems and pay ten times more per liter/ 3.6 Water demand to grow 40% by 2030 / 3.7 Green areas per inhabitant below the recommended levels and irregularly distributed (3.06 m^2/hab)/ 3.8 Public green areas are irrigated with drinking water/ 3.9 Presence of clandestine dumps that damage the marginal strips of the rivers/ 3.10 Economic impact of a severe water crisis on the economy / 3.11 Prehispanic irrigation canals are not part of the urban fabric.
4. Governance and Participation	4.1 Lack of coherence between water policies and related areas (sanitation, climate change, etc.)/ 4.2 Institutional fragmentation and lack of effective cross-sectoral coordination/ 4.3 The information is scattered and fragmented in different institutional storage systems in addition to infrequent data collection/ 4.4 The ANA does not integrate sectoral policies / 4.5 Significant mismatch between the delimitation of administrative boundaries and hydrological units/ 4.6 Overlapping and duplication of functions and regulations at regional and local levels/ 4.7 Entities lack adequate human, technical and resource capabilities/ 4.8 Lack of awareness with regard water management across all sectors/ 4.9 Lack of balanced participation of water users and conflicts of interest over water use/ 4.10 Autonomy of river basin authorities is still limited.

Table 13: Summary of weaknesses and threats

Source: Created by author, 2021

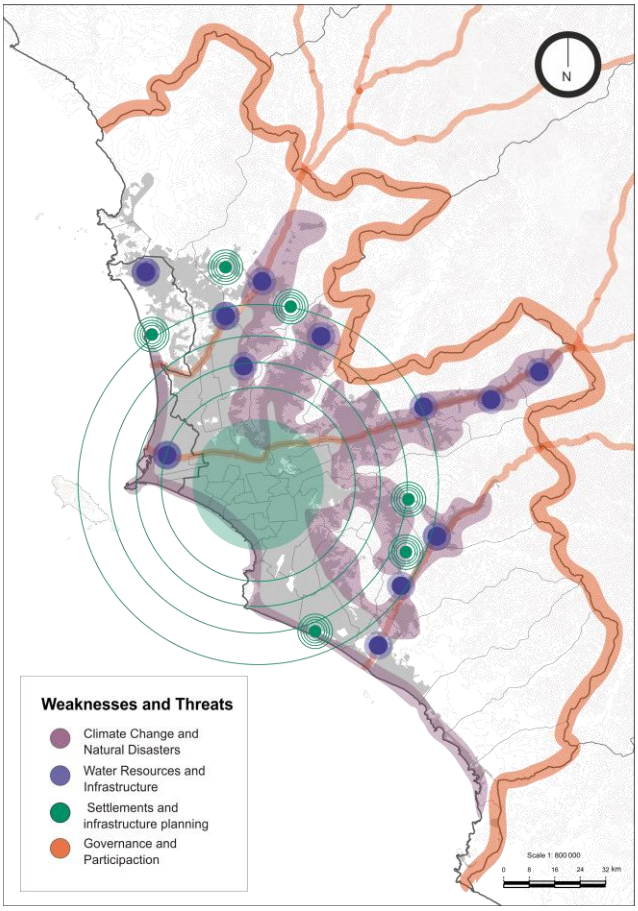


Figure 73: Map illustrating weaknesses and threats

Source: Created by author, 2021

4.8.2 Strengths and Opportunities for Lima – Baseline Scenario (Benchmark)

In addition to weaknesses and threats, key strengths and opportunities can also be identified. The presence of available blue infrastructure and natural and artificial green infrastructure provides the chance to take advantage of these spaces to provide ecosystem service benefits. Given the low levels of rainfall in the city, housing typologies in Lima have a high predominance of flat roofs, which could be a problem in the face of rainfall variability due to the impacts of climate change. Nevertheless, it can be seen as a great advantage as it can potentially be used as green roofs, thus increasing the green infrastructure space.

The other advantage of the city is its economic importance within the country. This aspect is crucial to justify the importance of implementing water-sensitive strategies and developing multi-scale projects. Geological conditions (the city's topography favors the natural water cycle) and moisture accumulation on the upper slopes (fog water collection) can also benefit the city.

A crucial factor in the successful development of a water-sensitive approach is the promotion of public participation. Grassroots organizations in the city setting are an essential driver of new projects, as cooperation between neighbors proves efficient and organized in the face of constraints. However, the capacity for self-management is not highly valued by public management bodies. Table 13 and Figure 74 provide a summary of the strengths and opportunities identified through the analysis.

1. Climate Change and Natural Disasters	1.1 The topography of the city / 1.2 High humidity levels and generation of fog in high areas / 1.3 Presence of porous soils to increase aquifer recharge
2. Water Resources and Infrastructure	2.1 Presence of blue infrastructure, rivers, and wetlands, within the city limits 2.2 Presence of pre-Hispanic water infrastructure/ 2.3 Potential for wastewater to increase water in the system
3. Settlements and infrastructure planning	3.1 Artificial urban spaces available for the development of strategies/ 3.2 Flat roofs in Lima
4. Governance and Participation	4.1 Neighborhood cohesion / 4.2 Economic center of the country/ 4.3 consolidated regulatory framework with multisectoral characteristics/ 4.4 approval of the Water Resources Law and the choice of Integrated Water Resources Management (IWRM) as the central axis/ 4.5 CHIRILU Basin Council

Table 14: Summary of strengths and opportunities

Source: Created by author, 2021.

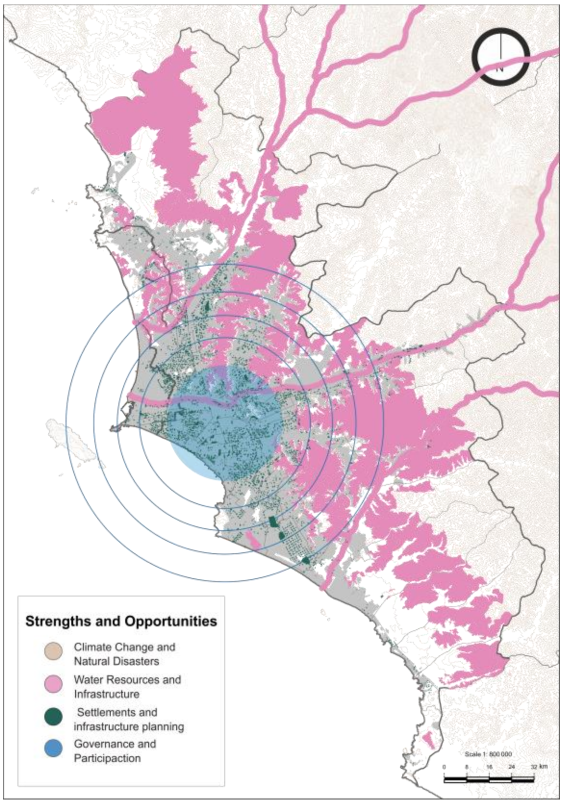


Figure 74: Map illustrating strengths and opportunities

Source: Created by author, 2021.

4.9 Discussion

The purpose of this section is to deepen the meaning, importance, and relevance of the results after the analysis in Metropolitan Lima and show how they relate to the literature review and best practices reviewed throughout the second and third chapters, respectively.

The analysis reveals that in the current water scarcity scenario in Lima, several factors exacerbate the crisis and, if not addressed, will lead to even more significant problems. Lima is a city with very particular natural characteristics; it is located in the middle of a coastal desert, its rainfall levels are scarce, and it has very varied geomorphology. Although they were taken advantage of in the past, all these inherent aspects are no longer so today. The city's water system is unstable because it depends on a centralized system concentrated mainly on surface sources with high contamination levels and significant supply losses. This situation makes water management vulnerable to the impacts of climate change. Estimates reveal that high variations in temperature and precipitation will further reduce water availability due to the melting of Tropical Andean Glaciers (TAG) and produce more frequent heatwaves, floods, and droughts impacting the city the population, production, and the ecological environment. Under this scenario, the water resources available today cannot meet the water demand of the inhabitants, industry, agriculture, and energy, and face rapid population growth with unfavorable projections for the next 15 years. This phenomenon has induced formal and informal urban sprawl processes throughout the city. The location of non-formal areas in peri-urban zones far from the center, coupled with the lack of government regulation, has widened the gap in access to essential water and sanitation services and impacted the contamination of surface water sources and the reduction in the volume of groundwater sources. The city's ecological areas have become fragile due to changes in land use, leading to changes in the city's landscape and increased population vulnerability to flooding and erosion in hillside areas.

Indeed, the results of the analysis suggest that, given the interrelationship between rapid population growth, climate change impacts, weak governance, and inequity in access to services, among others, Lima needs to implement a holistic approach that articulates integrated water management, urban planning, and green infrastructure management, as stated in the initial hypothesis of the research. However, the results also highlight the need to implement two modifications to the initial conceptual scheme. The first is on the conceptual basis of Lima's vulnerability to natural disasters associated with its location in a highly seismic zone. Thus, as shown in Figure 75, this factor requires special attention and is an independent element in the conceptual framework. Moreover, the second change focuses on the need to adjust its transition process towards a water-sensitive city.

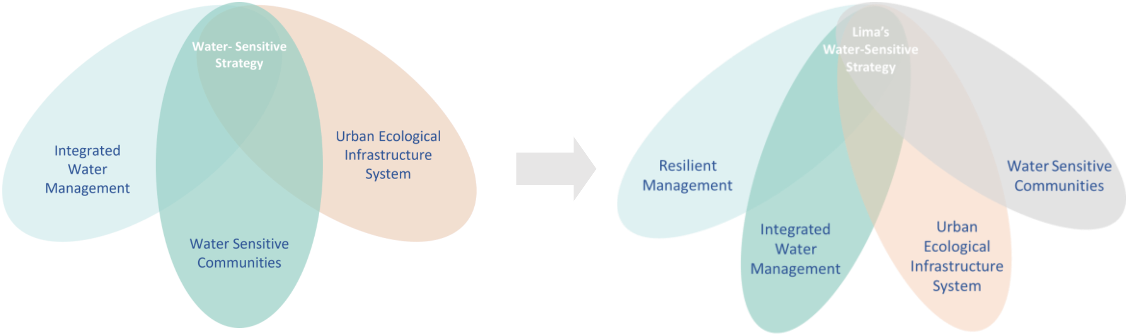


Figure 75: From the initial to the adapted conceptual diagram

Source: Created by author, 2021

4.8.1 Lima as a supply basin

The findings demonstrate that understanding the urban water cycle is crucial in semi-arid and low rainfall environments. In this need for a better understanding of the urban water cycle, the findings show tools such as UWMB to be promising in analyzing the metabolic processes of the natural and artificial sources that compose the water system of an urban environment.

However, it requires further research to be more consistent and less presumptive in developing contexts. The results after the application of the UWMB in Lima show a strong dependence on centralized systems since although a percentage of the demand is satisfied through decentralized ones, these are located in the upper areas of the basin, joining the surface runoff before entering the city, receiving pollutants along its route. This link between the city's water supply system and surface sources such as the Rimac, Chillon, and Lurin rivers is highly vulnerable to climate change given the origin of its waters in the Tropical Andean Glaciers (TAG), putting the balance of the urban water cycle at risk.

As shown in the literature review, traditional systems are less efficient in areas of water scarcity where drought events are prolonged and even more so with high levels of contaminants and losses in the system due to leakage (Arora *et al.*, 2015; Sapkota *et al.*, 2015). Indeed, meeting Lima's water needs requires a shift from traditional and ineffective systems to comprehensive and sustainable approaches. In that line, the metabolic analysis results applied to ML suggest the potential of wastewater to increase water in the city system. However, the source does not have sufficient potential to meet the city's total water demand, requiring its complementarity with other strategies. This finding confirms what was established in the literature review, the use of decentralized systems is not promising when they are exclusive given their limitations requiring their interaction with existing centralized systems and broader coverage, this implies developing diversified hybrid systems (Arora *et al.*, 2015; Sapkota *et al.*, 2015).

The analysis of implemented practices reveals that, in effect, the development of a hybrid system is one of the strategies that should be applied, seeking to transition towards sustainability, going beyond surface, runoff, or groundwater sources. Water management in Lima does not yet apply, which is why it is so vulnerable to the uncertainty of climate change and the decrease of water sources (Wong, Rogers, and Brown, 2020). The findings in the practice analysis also demonstrate that in semi-arid environments diversifying systems is optimal, highlighting the potential of wastewater recycling as an alternative source in the face of water scarcity and climate constraints. However, the analysis also shows that access to essential water services is covered in developed contexts. In this sense, the emphasis of its reuse is framed in a non-potable consumptive approach seeking to improve thermal comfort given the high temperatures and to cover the demand for irrigation of green areas. The generalization of the results to confirm the benefits of wastewater reuse in semi-arid environments is limited as long as the vision of developing contexts is not incorporated. Indeed, in cases like Lima, the needs to be covered are different, with priority being given to the coverage of primary needs. Although the findings are not conclusive regarding the benefits of reuse to cover these demands, the results emphasize that to reduce the levels of distrust inherent to the stigma that water reuse has in the population, a robust and transparent communication system is required. It is even noted that its levels of operation and acceptance are higher at local scales, an aspect that could be beneficial in Lima.

On the other hand, the findings also highlight the need in Lima to increase secondary and tertiary treatments in existing wastewater treatment plants (WWTPs) to increase their potential as an alternative source. The findings in practice recognize the multiple benefits of artificial wetland systems over traditional systems such as the existing ones in Lima by naturally eliminating pathogenic microorganisms more economically and occupying less space. This aspect also makes possible a better acceptance of wastewater reuse. The results reveal a need to integrate wastewater reuse systems into the urban environment through aesthetic strategies with social and recreational value and contribute to the ecological balance.

The background found in the literature review shows that the first pillar of water-sensitive cities focuses on accessing diversified water sources, understanding this as a combination of centralized and decentralized infrastructure that allows for a system of water collection, treatment, storage, and supply. In this sense, Lima's transition and its transformation to a supply basin implies diversifying its water sources, understanding its limitations in the face of low rainfall levels, and taking advantage of the opportunities offered by the reuse of wastewater for consumptive use through natural systems. It is also contributing to the semi-arid landscape and providing social and recreational value to the population. However, it is also noted that the centralized system must be strengthened.

4.8.2 Lima provides ecosystem services

The findings show that the city's ecological infrastructure, made up of blue and green elements - natural and artificial - is facing formal and informal urban expansion processes that, if left unattended, could produce dysfunctional effects on the already worn-out urban water cycle. This aspect is due to the loss of the benefits they provide to Lima; as shown in the analysis results, the hills are a natural habitat for endemic species, while the valleys, in addition to their productive contribution, stabilize the recharge aquifers as they are permeable soils. The findings confirm that wetlands are biodiversity hotspots in blue infrastructure and regulate watershed waters by purifying pollutants. At the same time, rivers are the primary source of water supply for the city.

Evidence from the literature review confirms that blue and green infrastructures (BGI), with greater emphasis on semi-arid environments, provide ecosystem services that regulate the biodiversity of the environment and the urban water cycle. They even offer resilient measures against the effects of climate change (Eisenberg *et al.*, 2013; Ahmed, Meenar, and Alam, 2019; Sun *et al.*, 2020). Indeed, the findings show that the loss of ecological infrastructure means that Lima loses its capacity to protect against floods and erosion on slopes and streams, increasing the population's vulnerability. Furthermore, in the face of heat island impacts, studies suggest that combining BGI with WSUD tools is beneficial in supporting evapotranspiration and boosting evaporative cooling. However, the benefits of implementing these strategies depend on the existing microclimates. In areas of higher humidity, shaded areas reduce up to 2 degrees of soil temperature, while in arid regions, the benefits are more significant but with species that are adapted to the environment (Coutts *et al.*, 2013). Against this, the findings in Lima show that there is no understanding of the context insofar as the city's green areas present coverage of species that consume high volumes of water and do not offer cooling benefits. They also show that green zones reinforce the city's fragmentation due to its heterogeneous distribution throughout the territory. On the contrary, the analysis of implemented practices reveals that homogeneously preserving green areas, balancing the ecological infrastructure, and improving landscapes are intangible in semi-arid zones. This aspect is confirmed by focusing on the reuse of wastewater to cover the irrigation demands of these areas and preferring the use of tools that offer aesthetic and ecological benefits, such as artificial wetlands instead of traditional systems.

The background found in the literature review shows that the second pillar of water-sensitive cities focuses on establishing harmony between the built and natural environment, recognizing through the integration of green and blue infrastructure its value to the balance. In this sense, Lima's transition and transformation to a city that offers ecosystem services imply preserving hills, valleys, wetlands, rivers, and equitable distribution of green and public areas. Thus, it could maintain the balance of the urban water cycle, buffer the effects of climate change and increase natural capital for its various benefits. However, it requires understanding the limitations of an environment with diverse geomorphology and precipitation levels as low as those that characterize the city.

4.8.3 Lima comprises water-sensitive communities

Lima's results show a need for strategic changes in a governance system at the national, basin, and local levels. Although the Peruvian context presents a consolidated regulatory framework with multi-sectoral characteristics, in practice, institutional fragmentation and discordance between administrative and hydrological boundaries reduce its capacity for action. This aspect confirms what was established in the literature review. A transition requires not only infrastructures but also sufficiently integrated, distributed, and flexible institutions being this, compared to developed environments with better stability, the most significant impediment in developing environments for its success and the emergence of undesirable alternatives (Brown, Rogers and Werbeloff, 2016; Wong, Rogers and Brown, 2020).

The precedents found in the review of practices demonstrate that developing robust multi-governance systems that host the water-sensitive approach requires bridging participation gaps by seeking the articulation of all societal actors. It also highlights that the decentralization of the governance system should be functional and spatial, establishing straightforward tasks and functions at the national, regional, and local levels and whose efforts add up to a shared vision for the future. According to the findings, this scenario is far from the context of Lima, where ministries at the national level pursue particular objectives. This situation is repeated at the basin scale. The mismatch between hydrographic units and regional and municipal administrative boundaries delimitation generates a fragmentation of roles that deepen the inability to establish a joint approach. At the local level, the findings show a high daily per capita consumption in central city areas, contrary to what is found in peri-urban areas where the values are low and with surprisingly high-cost overruns given the limitations of access to water and sanitation services. The results of the analysis of practices also confirm that the involvement of end-users and the community in decision-making ensures the system's success by sensitizing or informing, and making them part of the process. However, even in developed contexts, there are hierarchical nuances, which shows the complexity of this aspect.

The precedents found in the literature review show that the second pillar of water-sensitive cities focuses on engaging social capital and making them water-sensitive. In that sense, Lima's transition and transformation to a city that promotes water-sensitive communities imply establishing a multilevel governance system at both functional and territorial levels in line with watershed management and the promotion of sensitized communities involved in decision making. However, while these components in developing contexts such as Lima can be the basis for a comprehensive shift towards a multilevel model, this requires adaptation to the inherent socio-economic conditions of the city and the interrelated scales.

4.8.4 Lima provides equitable access

The background of Lima shows that the composition of the city is marked by a dysfunctional interaction between urbanized spaces and peri-urban areas, putting under pressure the ecological regions that promote the balance of the urban water cycle, this relationship being usual in developing contexts. The results also show that this coexistence implies different levels of progress between each space, which essentially translate into dissimilar water needs. Thus, in Lima's flat and urbanized areas, there is a need to reduce water demand, preserve and increase artificial green spaces through sustainable irrigation systems, and counteract the high levels of pollution to improve the quality of surface water sources. On the other hand, in the case of informal areas on the riverbanks and hillsides of the city, infrastructure is limited, and the existing gap in essential services needs to be urgently filled, in addition to increasing access to green and recreational areas given the current deficit. In Lima's ecological regions, it is necessary to establish a harmonious relationship with the habitable environments, seeking their protection and preservation.

The results suggest that the transformation towards a Water Sensitive City (WSC) implies transitioning taking as a starting point the Drained City stage as the approach is based on characteristics of a developed environment. In developing environments, no adaptations are suggested (Brown, Rogers, and Werbeloff, 2016). However, the findings show that this possibility is feasible insofar as the principles on which the transition is based; in practice, they only function as guidelines and can be adapted to the context in which they are to be inserted (Wong, Rogers, and Brown, 2020). Thus, they should contemplate the impact on the urban water cycle of factors specific to developing environments (Armitage *et al.*, 2014). Indeed, although there is still no practical evidence in emerging urban environments that confirms the need for an adaptation, the findings in Lima confirm that while flat and urbanized areas are seen as drained cities, equivalent to the state of any developed context, on the contrary, informal areas present a level that is still similar to that of a water supply city. In this sense, the implementation of a water-sensitive approach and the success of the transition as a future vision towards sustainability seeking to address water scarcity and guarantee Lima's water security implies not only transforming the city into a supply basin, providing ecosystem services, and promoting water-sensitive communities, but also recognizing the specific gaps that need to be bridged, as shown in Figure 76. Once the existing inequity in access to water and ecosystem benefits is addressed, the city could move forward in the transition.

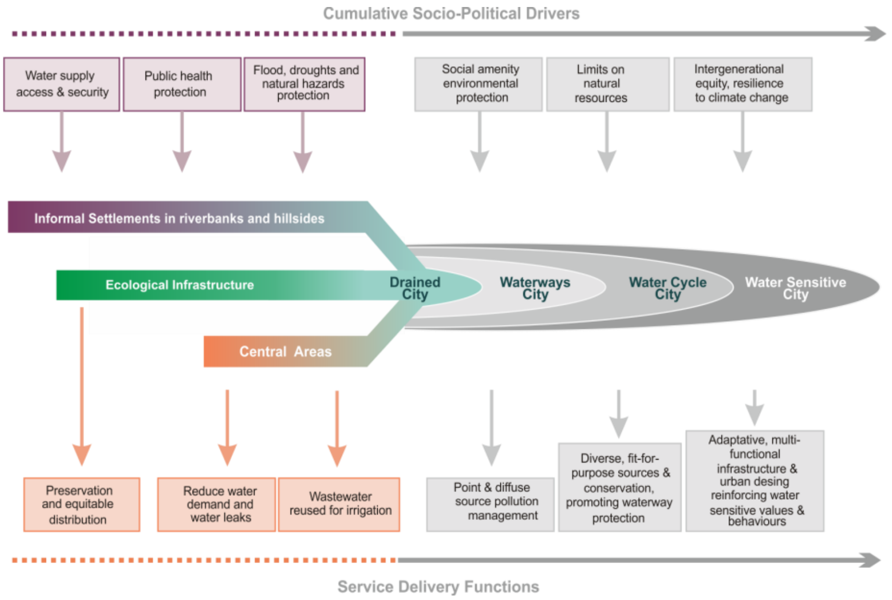


Figure 76: Lima's transition to a Water Sensitive City

Source: Created by author, adapted from Armitage *et al.*, 2014.

Chapter 5: Designing a WSUD Framework for Lima

In order to understand the urban water cycle in Metropolitan Lima, it is essential to highlight that all the variables mentioned in Chapter 4 are interconnected in one way or another. All the layers of the previous analysis should be understood as fundamental pieces of the urban water cycle. Given the geomorphological and climatic conditions of the city, everything that happens on the hillsides impacts the flat areas and vice versa, affecting not only the quantity but also the quality of water resources. The same happens at the level of hydrological basins; everything that occurs in the upper basins has relevance in the metropolitan area downstream. The main intention of the section is to design a contextualized water-sensitive strategic framework for the city's metropolitan area based on the opportunities and limitations found in the baseline. In that sense, it seeks to answer: What strategies can support the transition to the WSUD framework in Metropolitan Lima? The vision that will be presented should be understood as a formal contribution from the water and spatial aspects to transitioning Lima towards a water-sensitive city, understanding it as a future goal. From a practical point of view, the possibility of developing an ecological infrastructure (blue-green) network implies offering measures that solve problems at multiple scales, adapting to the specific characteristics of each sector of the city, and seeking to preserve the natural ecological balance. To this end, it is crucial to identify the different zones from a territorial approach, recognize their most urgent problems and link them with water-sensitive strategies. Thus, throughout the chapter, the city's zoning will be deployed as a comprehensive strategy for integrated water management. The main goals of each zone will be described, and the positive impacts on the urban water cycle. Towards the end of the chapter, the linkage of these areas with water-sensitive methods will be explained by developing a catalog of possibilities, and their applicability will be shown at three places in the city. Thus, the second part seeks to answer: How to adapt the strategy into a multi-scale design?

5.1 Vision: To create a sustainable, balanced water and ecological system in Lima by 2035

The transition to a water-sensitive city begins with a unifying vision seeking to restore the water and ecological balance both in Lima and at the level of the CHIRILU basin, as both areas of management are dependent on the territorial and hydrological aspects. Thus, all the challenges faced by the city and classified in the SWOT analysis concerning climate change and natural hazards, water infrastructure, and resources, accelerated population growth and its territorial and socioeconomic repercussions, and the governance system have been addressed. A thorough understanding of the Lima system's current conditions and elements that contribute to the problems described above constitute the baseline from which contrasts can be generated to quantify the impact of the future approach. It should be noted that the aspects of the governance system that must be modified to overcome the current challenges if the vision is to be achieved are explained in the chapter of Policy Implications (Chapter 6).

The Vision, A sustainable, balanced water and ecological system in Lima by 2035, is created under the premise that a Water Sensitive City (WSC) is seen as a future state. Therefore, the 2035 horizon is a propitious time frame to develop a robust framework to ensure the water sustainability of the city (Wong, Rogers, and Brown, 2020). Authors such as Ferguson and colleagues highlight the importance of envisioning future conditions when developing water-sensitive strategies to understand better and frame desired directions. In this sense, guiding principles are a crucial element that will guide the planning, investment, design, governance, and subsequent evaluation of a water-sensitive city (Ferguson, Frantzeskaki, and Brown, 2013). Similarly, the literature review of concepts such as WSC highlights the need to sustain the vision by employing the three inherent pillars of a water-sensitive city (Wong and Brown, 2009). This aspect can also be deduced from the literature review of other concepts such as IUWM and BGI. However, in the case of Lima, a multidimensional approach is also required to ensure cohesion between integrated water resources management, urban planning, ecological systems, and risks associated with natural disasters and climate change impacts, the latter being of utmost importance given the natural conditions of the city. In addition, the approach to the gap in access to water and sanitation services in peri-urban areas of the city should promote inclusion and equity in access to water. To this end, the vision seeks to raise awareness and improve coordination among the diverse actors in society to address the challenges associated with weak governance systems, institutional fragmentation, and lack of effective intersectoral coordination, and the mismatch between the delimitation of administrative boundaries and hydrological units.

5.1.1 Pillars

The Vision is consolidated into four pillars, as shown in Table 15, each with a specific but mutually dependent direction and representing long-term future aspirations: A Resilient Management, An Integrated Water Management, An Urban Ecological Infrastructure System, and A Water Sensitive Community. The pillars are written in the form of outcome statements for the 15-year vision of Lima as a water-sensitive city, each emphasizing a dimension of the water sensitivity paradigm tailored to the inherent characteristics of ML and the CHIRILU watershed that distinguishes it from the conventional model.

Aspect	Vision Pillar	Results statement
Climate Change and Natural Disasters	A Resilient Management	A Vision that understands the implications of climate change and is prepared for a range of possible future scenarios and minimizing the natural risks to which the city is exposed.
Water Resources and Infrastructure	An Integrated Water Management	A Vision that recognizes the value of water and takes advantage of local biophysical characteristics to diversify its sources and establish sustainable management of the water cycle in harmony with the ecological environment.
Settlements and infrastructure planning	An Urban Ecological Infrastructure System	A Vision that promotes the integration of the spatial qualities of water in the urban built environment with existing ecosystems offers social, ecological, and economic benefits to the urban and peri-urban population and emulates the pre-Hispanic's successful historical water management practices period.
Governance and Participation	A Water Sensitive Community	A Vision that ensures that socio-political capital from all sectors is sensitized, empowered, and committed to providing safe and sustainable water access.

Table 15: Pillars of the Vision for Lima and the CHIRILU basin.

Source: Created by author, 2021.

5.2.2 Principles

To implement concrete actions that uphold the four pillars described above, the Vision includes eleven guiding principles, as shown in Table 16.

Pillar	Principles	Description
1	I. Risk management for the city's mitigation and adaptation to climate change.	This principle aims to create strategies that mitigate the impact of climate change and increase resilience.
	II. Reducing vulnerability to natural disasters (spatial, social, and economic).	This principle emphasizes the need to be prepared for the natural disasters to which the city and the basin are constantly exposed by reducing the magnitude of the impact and vulnerability of the population and infrastructure through water-sensitive management of space.
2	III. Recognizing water as a valuable resource by diversifying its sources and reuse	This principle aims to diversify the city's water sources by recognizing existing potentialities and strengthening the central system to transform towards a more resilient hybrid system.
	IV. Protecting, conserving, and improving the integrity (quantity and quality) of natural Water Bodies (rivers, aquifers), anthropogenic systems (infrastructure).	In semi-arid environments, the role played by blue and green infrastructure in the balance of the urban cycle is crucial. Thus this principle emphasizes the need to protect the quality and quantity of all elements of green infrastructure by promoting the aesthetic and ecosystemic benefits they can lend to the urban environment.
	V. Understanding the implications of inherent natural conditions: low rainfall, irregular flows, desertic environment, topography, humidity.	A water-sensitive city in a semi-arid environment requires understanding the water cycle to minimize risks and enhance opportunities for natural site conditions. Thus, the principle ensures that strategies are adapted correctly and sustainably throughout the watershed and the city.
3	VI. Ensuring a reliable, safe, and cost-effective water supply for all uses today and future	This principle promotes safe and equitable access to drinking water and secondary benefits by improving inhabitants' quality of life by eliminating gaps in access to essential services.
	VII. Ensuring water management planning is precautionary and recognizes equity,	A water-sensitive city requires efficient and sustainable land management practices to manage the city's population growth and ensure that urban expansion does not have a negative impact on the environment and its inhabitants. This principle refers to establishing a connection

	biodiversity conservation, and ecological integrity.	between the ecological infrastructure and the urban environment promoting equitable access and enjoyment throughout the territory.
	VIII. Revaluing ancestral systems and restoring existing infrastructure.	This principle emphasizes the need to revalue the ancestral methods that once maintained the water balance of Lima and the watershed and today are forgotten and disconnected from the urban fabric.
4	IX. Strengthening water governance: institutional, financial, human, and social capacity.	This principle emphasizes cohesion among all stakeholders. This factor will require strategies that create accountability and transparency at all levels of governance and the full participation and inclusion of communities and stakeholders in the private and public sectors.
	X. Improving water awareness amongst all stakeholders and facilitating behavior change.	This principle emphasizes the need to ensure that communities are aware of their role in creating a healthy watershed and city with sustainable access to water today and in the future. It is expected to inspire a unified effort among communities to change habits through educational programs to reduce demand by promoting a water-sensitive culture.
	XI. Integrating knowledge (scientific and ancestral) and community values in decision making.	It promotes informed and empowered end-users and communities at all scales of intervention and seeks to involve them in decision-making processes. The principle also emphasizes the need for articulation between technological advances and pre-Hispanic methodologies to develop new solutions.

Table 16: Principles of the vision for Lima and the CHIRILU basin.

Source: Created by author, 2021.

5.3.1 Vision Pillar 1: A Resilient Management

The CHIRILU basin and mainly Metropolitan Lima need to face the impacts of climate change and be prepared for uncertainty by implementing adaptation and mitigation strategies to increase the city's resilience and the basin, as shown in Table 17. Water management (collection, treatment, and transport) currently requires large amounts of energy and sometimes consumes much water to generate. Although it could be thought that climate change and water management are isolated elements, the truth is that comprehensive solutions must be sought to reduce the generation of greenhouse gases associated with traditional water management. Only in this way will it be possible to maintain the balance of the water cycle and increase resilience in the future (Strategy 1.1). Measures at different scales of intervention can be incorporated, such as: to establish a GHG generation and climate risk assessment system in each of the system's existing infrastructures, create a sludge reuse program to fertilize agricultural areas, implement a biogas program to supply the city's energy and fuel system, install solar panels on drinking water treatment plants and wastewater treatment plants to provide them with electricity, install efficient irrigation systems (sprinkler irrigation) in public green areas, plant low water consumption vegetation covers such as aptenia and increase natural shade areas, and create green façade systems in urban areas.

Given the seismic and climatic conditions, the urban environment is also highly prone to natural disasters, in some cases due to events exacerbated by climate change such as droughts and floods. In this regard, it is necessary to minimize the risks to which the population, the ecological system, and infrastructure are exposed by establishing prevention strategies (Strategy 1.2). In high-risk zones, the transformation of existing infrastructure (natural and anthropogenic) is also required, incorporating elements to secure slopes and reverse the erosion of streams and coastal areas (Strategy 1.3). Measures at different scales of intervention can be incorporated, such as: to create a Disaster Contingency Plan at the CHIRILU and Lima Basin level, implement an Early Warning system in case of disasters, and geolocation of safe zones, create an insurance policy system against floods, droughts, and landslides. Other measures also include: to implement a River Revitalization Program creating multifunctional dikes with safe flood zones, create a comprehensive maintenance program and increase the number of water storage tanks and irrigation canals in the city, revegetate the waterfronts in the coastal areas to stop erosion and in the ravine areas implement in the high areas a runoff containment system to stop and store water while in the low areas create permeable zones.

Strategies
1.1. Integrate greenhouse gas reduction in water management
1.2. Establish strategies for prevention
1.3. Convert urban infrastructure (gray and green) in high-risk zones in water-sensitive areas.

Table 17: A Resilient Management strategies

Source: Created by author, 2021.

5.3.2 Vision Pillar 2: An Integrated Water Management

Lima requires a shift from traditional systems to integrated and sustainable approaches, especially given its dependence on centralized systems, its condition as a semi-arid environment without rainfall, and the need to cover water gaps for irrigation in the flat area and access to water services in the upper area of the territory. In this sense, the diversification of sources should contemplate, as shown in Table 18, a model that incorporates the collection, treatment, saving, and reuse of wastewater, enhancing the natural and artificial sources that make up the urban water cycle, considering the conditioning factors to avoid their alteration (Strategy 2.1). However, the hybrid system to which this transformation aim requires a robust central system that allows the annexation of other sources with great potentials, such as wastewater. Thus, it is necessary to recover the water lost in the current supply system, reduce pollutants in the sources and upgrade the wastewater treatment system currently operating in the city (Strategy 2.2 and 2.3). Measures at different scales of intervention can be incorporated, such as: to implement a comprehensive maintenance and technology improvement program for the existing wastewater treatment plants in the city, design a network of wastewater treatment plants and articulated irrigation canals, create a maintenance program for the piping system and update the existing one, and establish a program for the recovery of mounds in the upper zone to store water and increase the recharge of the aquifer. Other measures include to develop a water quality monitoring program, to establish maximum residue values for pharmaceuticals and other heavy metals not currently contemplated in the blue bodies, to control the use of pesticides in the agricultural valleys, and to reduce mining, industrial, municipal and domestic contamination points and illegal groundwater extraction points. In addition, create a system of artificial wetlands and expand the existing natural wetland areas are other measures that can be incorporated.

On the other hand, the city's topographic and climatic factors, together with its proximity to the coast, generate very particular conditions in the higher areas of the hillsides where humidity levels can reach 100%. Many people in the area take advantage of this by collecting water from the fog, a source that can be highly beneficial given its sustainability and low cost (Strategy 2.4). Measures such as create a program to install fog catchers in the high areas of Lima on a large scale for collection, treatment, and distribution for consumptive uses can be incorporated.

Strategies
2.1 Establish a water management model that considers the collection, treatment, saving, and reuse of wastewater.
2.2 Reduce polluting sources of water bodies and infrastructure
2.3 Maximize the use of decentralized wastewater and reduce system water losses.
2.4 Develop and implement other alternative sources of water adapted to the inherent characteristics: fog

Table 18: An Integrated Water Management strategies

Source: Created by author, 2021.

5.3.3 Vision Pillar 3: An Urban Ecological Infrastructure System

Lima's ecological infrastructure faces urban expansion and land-use change processes, reducing its surface area and impacting the urban water cycle. In this sense, as shown in Table 19, the ecological infrastructure, whether natural or artificial, must be articulated, integrated, and increased in the urban environment of the city and the watershed, promoting the creation of multifunctional public spaces that seek to cover the city's current deficits and encourage sensitivity to water (Strategy 3.1 and 3.3). However, to sustain them over time, sustainable irrigation systems should be provided to reduce dependence on drinking water sources for this purpose. If pre-Hispanic irrigation systems exist in the vicinity, their incorporation into the local fabric should be promoted (Strategy 3.2 and 3.4). Measures at different scales of intervention can be incorporated, such as: eliminate clandestine drinking water points for municipal irrigation, regulate the tariff system for consumptive water use, create an irrigation system for artificial green areas with recycled wastewater, and create recreational areas by unclogging and rehabilitating existing irrigation canals as well as increasing the network. Other measures also include create a National Planning Institute to regulate land management, implement a system of cleaning biotopes and create reforestation programs in the upper areas of the basin, in the hillside area promote the spread of amancaes flower and xerophyte species and in the lower area with endemic tree species such as the Molle Serrano (*Schinus molle*), the Huaranguay (*Tecoma stans*) and the Tara (*Caesalpinia spinosa*).

Strategies
3.1 Maximize the aesthetic benefits of water planning in the urban environment equitably.
3.2 Reduce potable water consumption for non-necessary uses and regulate unjustified additional costs for necessary uses
3.3 Establish integrated planning between natural ecosystems, green infrastructure (natural and anthropogenic), and urban water management.
3.4 Integrate ancestral systems and infrastructure to the water system.

Table 19: An Urban Ecological Infrastructure System strategies

Source: Created by author

5.3.4 Vision Pillar 5: A Water Sensitive Community

Lima needs to make strategic changes in its governance system at the national, basin, and local levels, given the high degree of institutional fragmentation and discord between administrative and hydrological boundaries. In addition, there is no water culture given the high rates of per capita water consumption in a sector of the population. In this sense, to ensure that the socio-political capital of all sectors is sensitized, empowered, and committed and thus guarantees safe and sustainable access to water, it is necessary to contemplate multi-sectoral planning with clear responsibilities and under a common objective (Strategy 4.1 and 4.4). In addition, as shown in Table 20, it is necessary to involve all the actors of civil society, public and private sector, by providing spaces for participation and managing a water culture in the community (Strategies 4.3 and 4.5). Multiple measures can be incorporated at different scales of intervention; more precise detail of them can be found in Chapter 6.

Strategies
4.1 Establish cross-sectoral strategic planning by defining specific roles and obligations.
4.2 To build capacity in terms of workforce and skill profiles.
4.3 Involve stakeholders equitably through a holistic and integrated approach.
4.4 Consolidate the information and knowledge base on current and future risks.
4.5 Establish water education and awareness mechanisms in the community.

Table 20: A Water Sensitive Community strategies

Source: Created by author

The above principles and strategies can be used as a comprehensive basis for guiding the transition to a water-sensitive city in Lima as well as other developing and semi-arid cities as it addresses the different dimensions of water scarcity, allowing the adaptation of measures to the context of each urban environment.

5.2 Transitioning: From a Baseline to an Optimistic Scenario

Based on the literature review, it is possible to assume scenarios that contemplate a conservative implementation of the water-sensitive approach and a scenario where implementation is maximized (Brown, Rogers, and Werbeloff, 2016; Meng and Kenway, 2018). Although this section is based on assumptions, simplification of individual indicators, and an adaptation of the proposed percentages and scenarios compared to what is established in the literature, it is determined whether applying the approach will cover both the current demand (1,144 Hm^3) and the future demand (1,601 Hm^3) which, as mentioned in Chapter 4, is presumed to increase in the next 15 years.

5.2.1 Baseline, no intervention

In the base scenario, the weaknesses shown in Chapter 4 have not been corrected, and the opportunities have not been taken advantage of, implying that no vision has been implemented. Under this level, Lima presents a water scarcity scenario and cannot guarantee water resources in the future, with a supply of 1,066 Hm^3 and a demand of 1,601 Hm^3. Therefore showing 425 Hm^3 of deficit. Additionally, the results of the UWMB and the analysis of Lima's ecological infrastructure confirm 100% centralization of the water system, and 30% of the water supply is lost due to leaks in pipes and illegal connections. Moreover, it settles that only 7% of water is recycled, 11.6% of wastewater is not treated, 1.5 million inhabitants do not have access to services, the existence of 3.06 m^2 of green area per capita, among many other findings.

5.2.2 Conservative WSUD Approach

A conservative scenario involves implementing the water-sensitive Vision in Lima but presenting some undesirable alternatives along the way, such as roadblocks or setbacks. This scenario assumes only a 10% to 20% improvement over the baseline. Applying these assumptions would mean that using 33% of the potential resulting from UWMB in wastewater recycling and reuse could reinsert up to 288.6 GL per year (288.6 Hm^3) into Lima's water system, covering one-fifth of the gap in access to services, and increase the city's green area to 3.9 m^2, for example. Although this scenario represents a clear advance in the transition, it is insufficient to meet Lima's total future water demands.

5.2.3 Optimistic WSUD Approach

As shown in Figure 77, an optimistic scenario implies transitioning as planned, articulating efforts to implement and comply with the established strategies. This scenario assumes improvements between 30% and 50% concerning the baseline. Applying these assumptions, using 80% of the potential resulting from UWMB (rainwater + rainwater + recovery of water losses + recycling and reuse of wastewater), up to 721.5 GL per year (721.5 Hm^3) could be reinserted into Lima's water system. It could also cover at least half of the gap in access to water and sewage services and increase the green area per capita to at least 5 m^2. While the calculations are purely based on assumptions and require further introspection and analysis, this reinforces that Lima requires drastic changes from a holistic view if it really wants to overcome the current water crisis and become a sustainable and resilient city in the future.

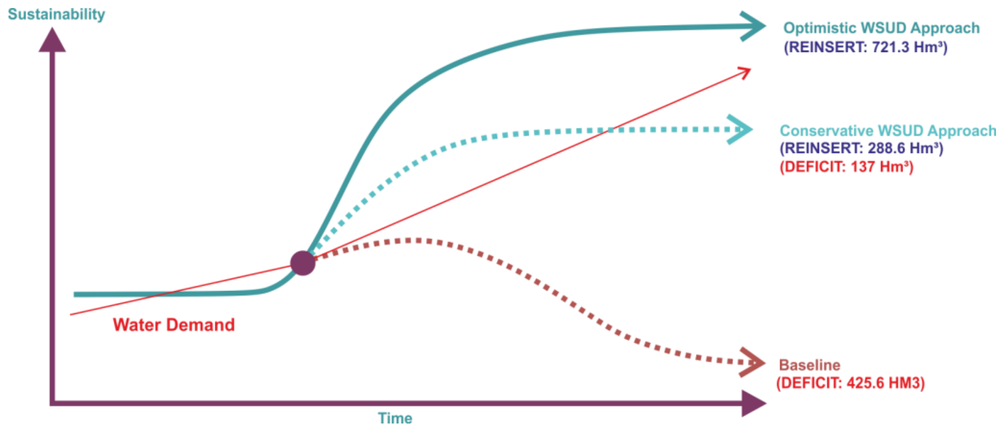


Figure 77: From a Baseline to an Optimistic Scenario

Source: Created by author, adapted from Brown, Rogers, and Werbeloff, 2016.

5.3 Overlapping layers in the territory

From the territorial aspect, to carry out the strategic objectives set out in the Vision, it is necessary to analyze Lima from an urban perspective. As established in the Discussion Section (see Chapter 4), Lima's background reveals that the city comprises urbanized spaces associated with the WSC Drainage City level and peri-urban areas (Supply City) with different water needs. In this sense, to apply the most appropriate WSUD measures and tools for each zone that composes the city, it is necessary to superimpose different layers analyzed throughout Chapter 4, as shown in Figure 78. Thus, urban typologies have been classified according to four aspects: relationship concerning water infrastructure (natural and artificial), access to ecological infrastructure (natural and artificial), urban expansion typology (formal and informal), and topographical conditions within the territory of Metropolitan Lima, all explained throughout Chapter 4.

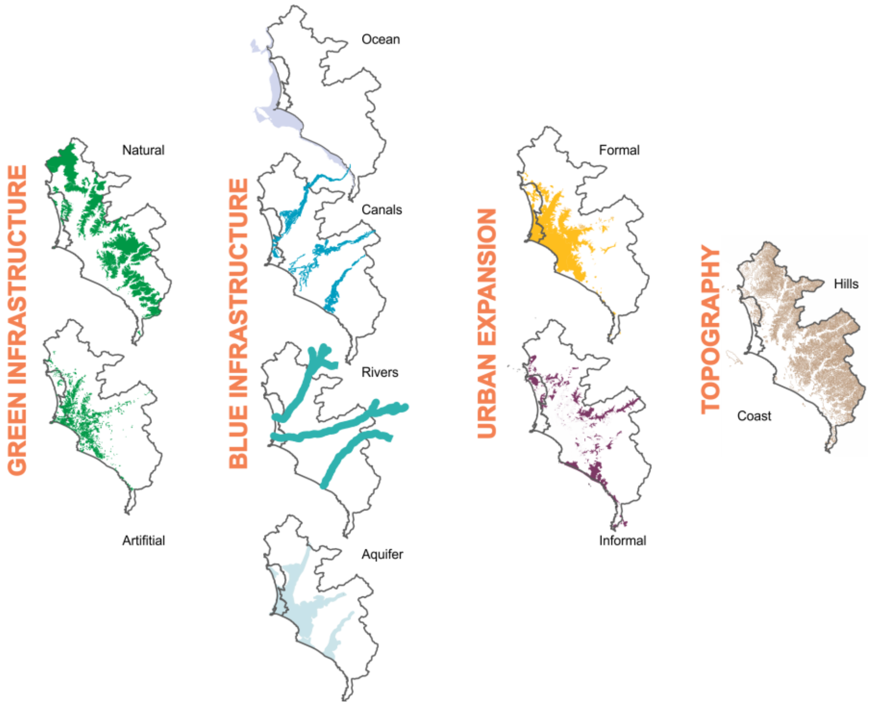
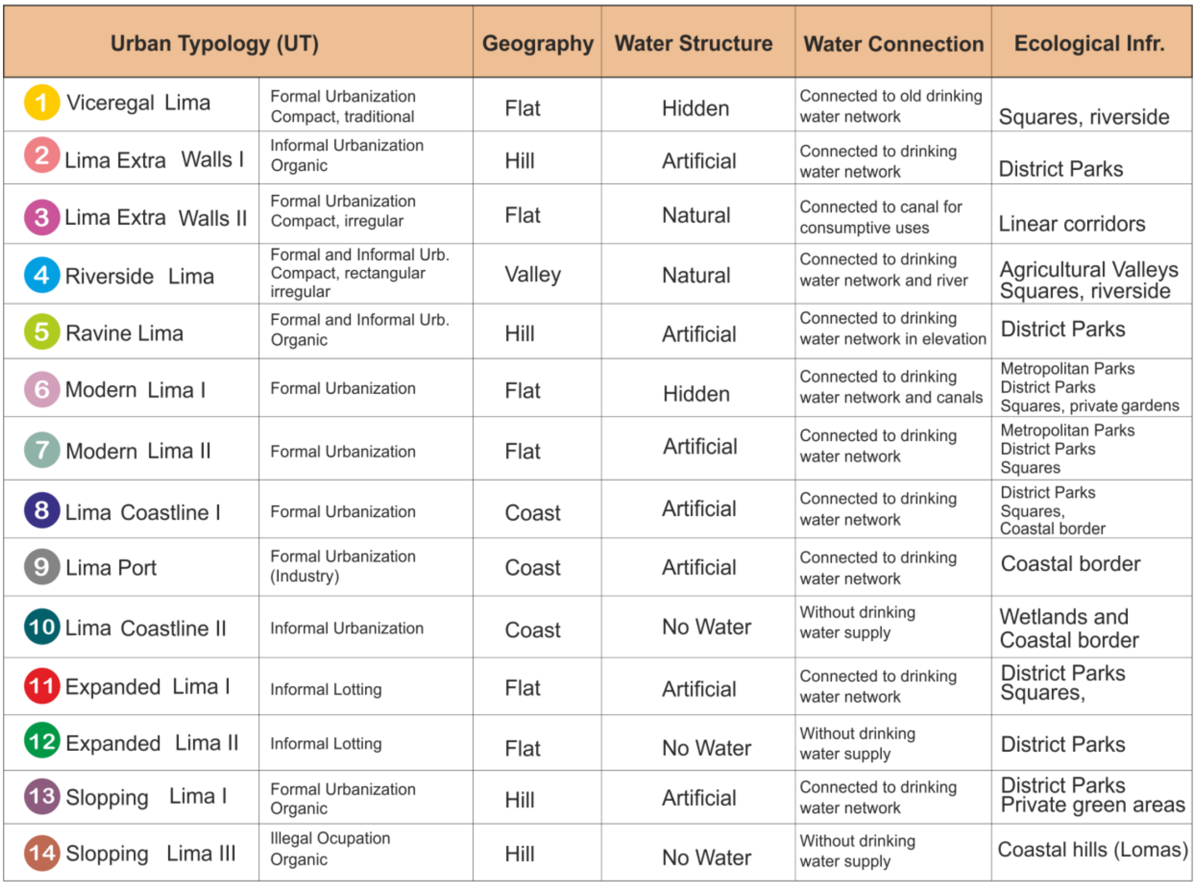


Figure 78: Overlapping layers in ML

Source: Created by author, 2021.

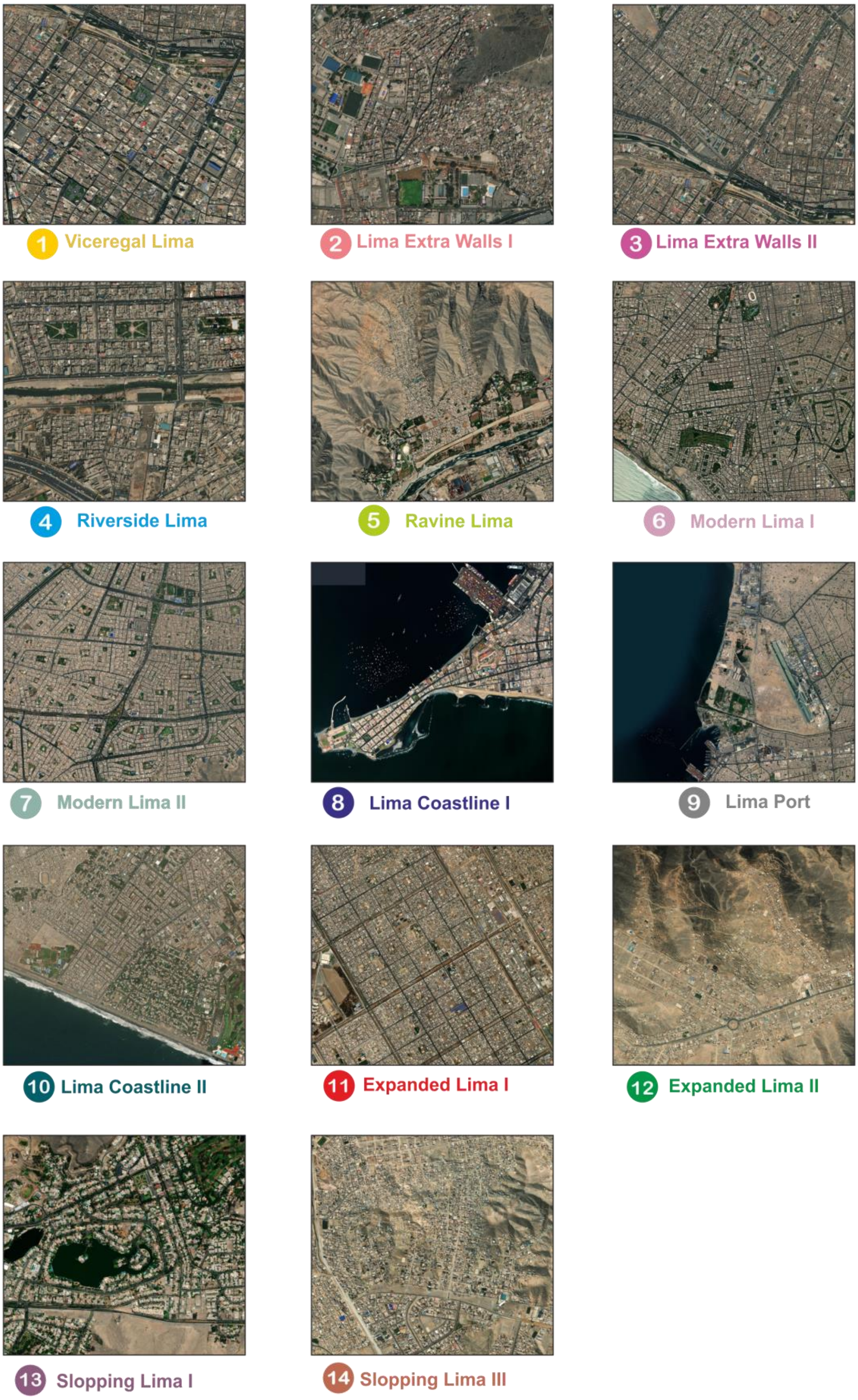
As shown in Table 20, in the water infrastructure layer, the components refer to the presence or proximity of a blue element, either natural or artificial. These factors are 1. Natural Water: Rivers or open-pit canals, 2. Artificial Water: Water and sewage system, 3. Hidden Water: Hidden canals and irrigation ditches system, 4. No Water: No water and sewage system and no proximity to natural water and as an exceptional case (*) the proximity to a WWTP. The presence or closeness to green infrastructure, natural and anthropogenic, has been considered on the second layer of ecological infrastructure. Thus, among the factors are Coastal Hills (Lomas), Metropolitan Parks, Coastal Borders (coastline), River Border (riverside), District Parks, Wetlands, Private Green Areas, Squares (Plazas), and areas under high tension electricity towers. Concerning the layer of urban typologies, three factors have been used to classify them: first, whether it is an urbanized or informal area; second, about physical characteristics such as compact, regular, irregular, or organic organization. The third factor is whether or not the site has access to water and sewage services. If not, if it is connected to a river or a pre-Hispanic irrigation canal. In addition, four characteristics are used in the topography layer: areas in front of the coast, flat areas, areas in the valley, and areas on slopes. Figure 79 shows aerial images of each zone, while Figure 80 shows the spatial location of each urban typology within the city.



Urban Typology (UT)		Geography	Water Structure	Water Connection	Ecological Infr.
① Viceregal Lima	Formal Urbanization Compact, traditional	Flat	Hidden	Connected to old drinking water network	Squares, riverside
② Lima Extra Walls I	Informal Urbanization Organic	Hill	Artificial	Connected to drinking water network	District Parks
③ Lima Extra Walls II	Formal Urbanization Compact, irregular	Flat	Natural	Connected to canal for consumptive uses	Linear corridors
④ Riverside Lima	Formal and Informal Urb. Compact, rectangular irregular	Valley	Natural	Connected to drinking water network and river	Agricultural Valleys Squares, riverside
⑤ Ravine Lima	Formal and Informal Urb. Organic	Hill	Artificial	Connected to drinking water network in elevation	District Parks
⑥ Modern Lima I	Formal Urbanization	Flat	Hidden	Connected to drinking water network and canals	Metropolitan Parks District Parks Squares, private gardens
⑦ Modern Lima II	Formal Urbanization	Flat	Artificial	Connected to drinking water network	Metropolitan Parks District Parks Squares
⑧ Lima Coastline I	Formal Urbanization	Coast	Artificial	Connected to drinking water network	District Parks Squares, Coastal border
⑨ Lima Port	Formal Urbanization (Industry)	Coast	Artificial	Connected to drinking water network	Coastal border
⑩ Lima Coastline II	Informal Urbanization	Coast	No Water	Without drinking water supply	Wetlands and Coastal border
⑪ Expanded Lima I	Informal Lotting	Flat	Artificial	Connected to drinking water network	District Parks Squares,
⑫ Expanded Lima II	Informal Lotting	Flat	No Water	Without drinking water supply	District Parks
⑬ Slopping Lima I	Formal Urbanization Organic	Hill	Artificial	Connected to drinking water network	District Parks Private green areas
⑭ Slopping Lima III	Illegal Ocupation Organic	Hill	No Water	Without drinking water supply	Coastal hills (Lomas)

Table 20: Urban Typologies in ML

Source: Created by author, adapted from Espinoza and Fort, 2020.



1 Viceregal Lima

2 Lima Extra Walls I

3 Lima Extra Walls II

4 Riverside Lima

5 Ravine Lima

6 Modern Lima I

7 Modern Lima II

8 Lima Coastline I

9 Lima Port

10 Lima Coastline II

11 Expanded Lima I

12 Expanded Lima II

13 Slopping Lima I

14 Slopping Lima III

Figure 79: Aerial images of urban Typologies in ML

Source: Created by author, adapted from Zoom Earth, 2021.

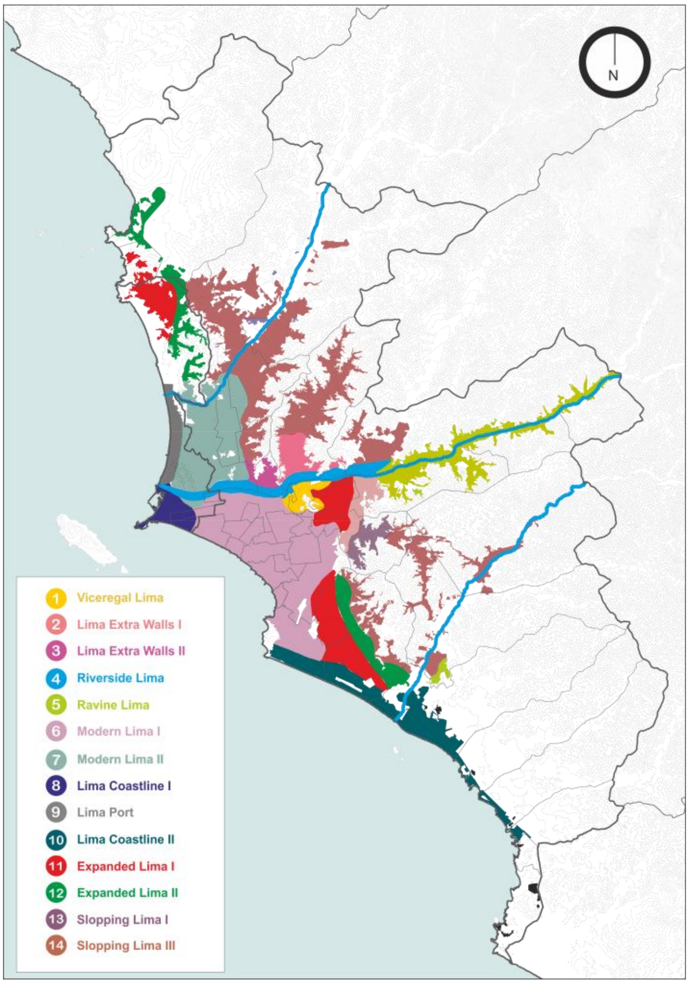


Figure 80: Spatial location of urban typologies within ML

Source: Created by author, 2021.

The overlapping layers, coupled with the challenges highlighted in the previous chapter and the classification of urban typologies, allow for a better understanding of the primary water needs of the arid city of Lima. As part of the overall vision of restoring the city's water cycle balance, the Vision has set out five interventions, as shown in Figure 81: (1) Collect and Reuse, (2) Delay and Conduct, (3) Treat and Reuse, (4) Expose and Reuse, and (5) Protect and Clean.

For each intervention, different WSUD tools and measures are applied with the primary objective of promoting the treatment and reuse of wastewater for potable consumption in the upper areas of the slope (peri-urban) and non-potable consumption (irrigation of the green and agricultural regions) in the flatter areas. In addition, in medium slope areas where there is a greater danger of landslides in natural disasters, the objective is to re-launch the natural flow of water from the upper zone towards the flat plains of the city, minimizing dangers and increasing the percentage of treated runoff. In the urbanized flat areas connected with the pre-Hispanic canals, the objective is to incorporate them into the urban fabric and water network by promoting the aesthetic qualities of the water and encouraging the irrigation of public green areas with treated water. In coastal areas, there is an imperative need to minimize the risk of flooding in the face of rising sea levels due to the effects of global warming and reduce the polluting agents of the tributaries to the ocean.

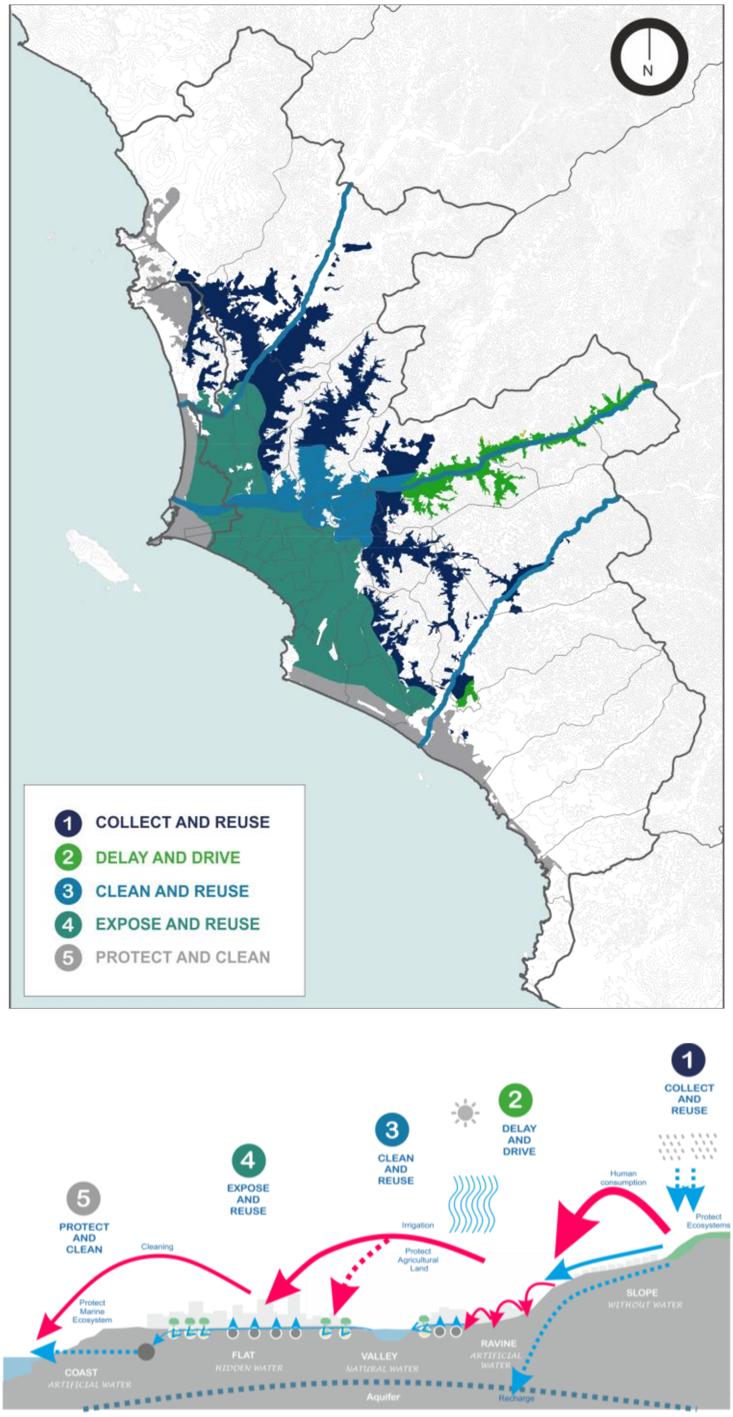


Figure 81: From Plan to Action

Source: Created by author, 2021.

This conceptual map sets out the main goals for each of the 14 zones identified in Metropolitan Lima as part of an effective strategy for a water-sensitive approach by recognizing the specific gaps that need to be bridged.

5.3.1 Catalog of Options

Based on the five interventions: (1) Collect and Reuse, (2) Delay and Drive, (3) Clean and Reuse, (4) Expose and Reuse, and (5) Protect and Clean exposed a catalog of spatial solutions is defined through the adaptation of the water-sensitive tools outlined in Chapter 2 to the inherent conditions, ecological infrastructure, and urban fabric of Lima. As shown in Figures 82 and 83, the catalog development will help Lima transition to a Water Sensitive City and promote the extension of the strategies in the future to other city areas.

Figure 82: Catalog of water-sensitive tools at macro and meso-scale

Source: Created by author, 2021.

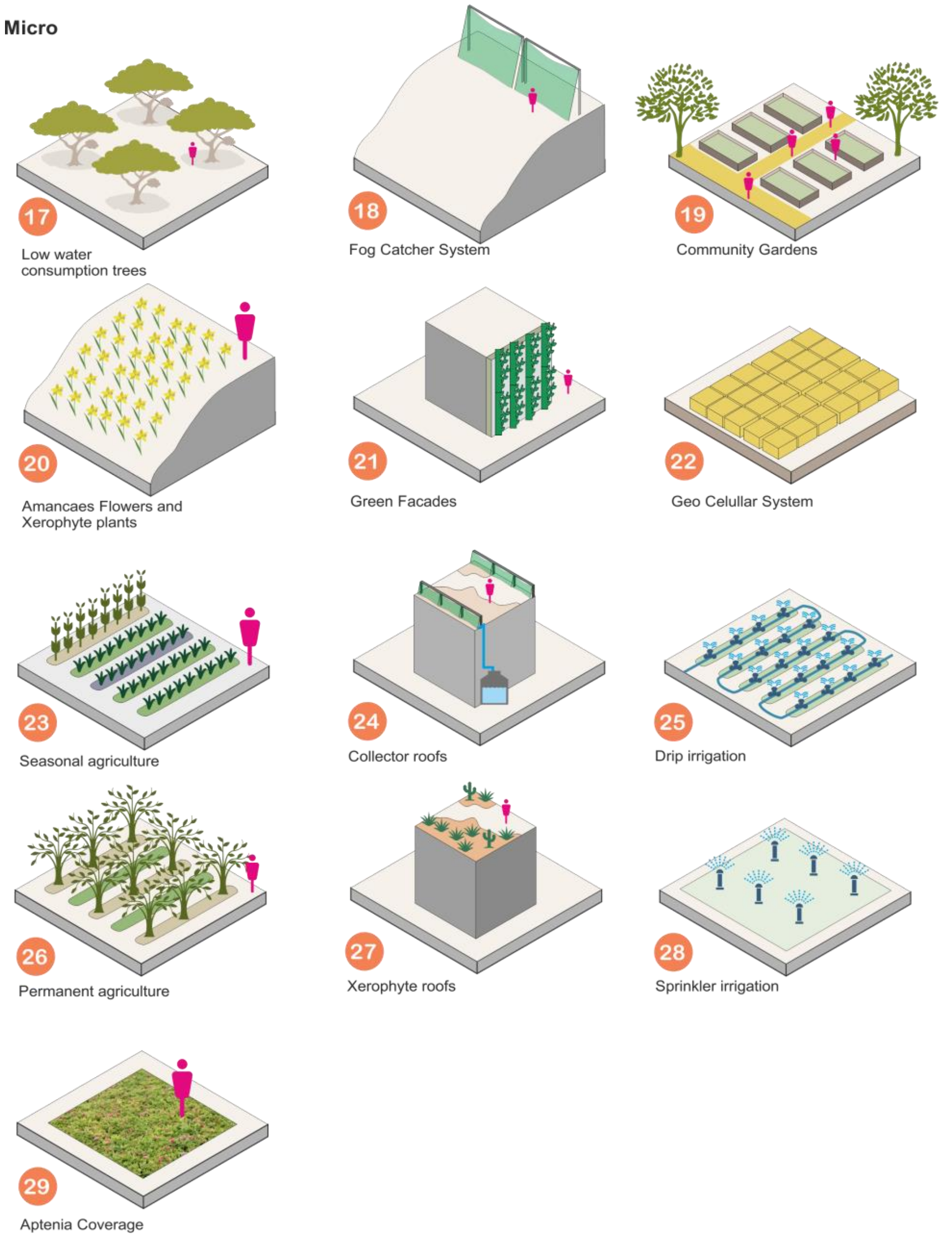


Figure 83: Catalog of water-sensitive tools at micro-scale

Source: Created by author, 2021.

- Intervention Zones

The three intervention zones are located within the urban limits of Metropolitan Lima. They have been selected based on the analysis carried out in Chapter 4 and the overlapping of the resulting layers and urban typologies. Each zone is located in different city areas, and, given their size, they have been cataloged at the macro, meso, and micro scales, as shown in Figure 84.

The Rimac River, selected as a macro-scale proposal **(A)**, crosses a large portion of the city and flows into the Pacific Ocean. It is also the primary source of Lima's water supply and paradoxically is one of the most urgent areas for intervention given its riverside's environmental and social vulnerability. On the other hand, in the case of the network of pre-Hispanic canals, selected as a meso-scale proposal **(B)**, they cross a significant number of districts throughout the territory. In this sense, the proposal could be replicated in other areas of the network. In addition, a zone with specific characteristics was selected on the left bank of the Lurin River **(C)**. The informal settlement Quebrada Verde is surrounded by the last extensions of agricultural valleys of the city as well as coastal hills in the upper areas.

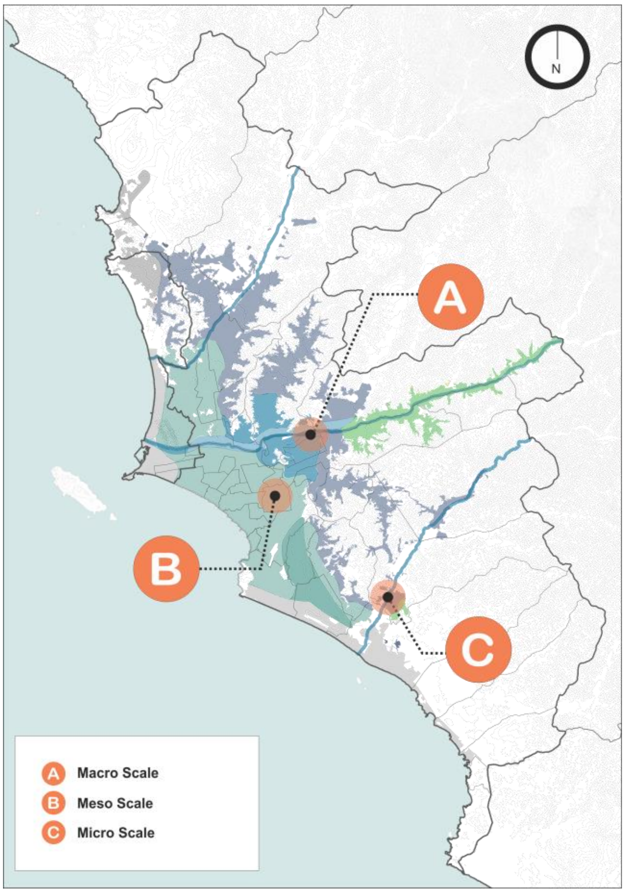


Figure 84: Areas of interventions in ML

Source: Created by author, 2021.

5.3.2 Macro-scale: Reintegrating the Rimac River

The area selected for the elaboration of the proposal is the strip of the Rimac River between the Atarjea area and the areas inhabited by the Cantagallo Community, as shown in Figure 85. From the positive aspects, it is a central area with good connectivity (railroad, the Metropolitano, the Metro Line, Linea Amarilla, Evitamiento), the existence of the unused regions on the banks of the river, and a vast network of small-scale public areas in the vicinity, and the presence of wastewater treatment plants in the area. On the negative side, however, informal areas have no water and sewage connections, poor water quality, lack of biodiversity, and illegal dumping. Therefore, the main goal will be CLEAN and REUSE (3).

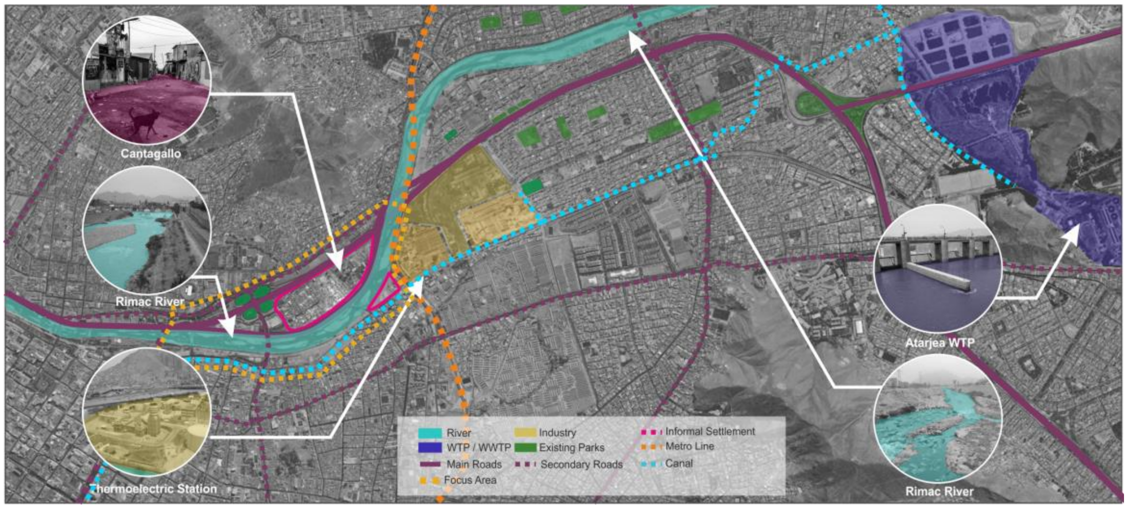


Figure 85: Characteristics and surroundings of the area of interest of the Rimac River

Source: Created by author, adapted from Zoom Earth, 2021.

As shown in Figure 86, the proposal seeks to recover the riverbanks by creating a multifunctional linear park. During low water levels, the terraces can be used as public spaces. On the other hand, during periods of high-water level, they would function as containment dikes to protect the surrounding neighborhoods. Additionally, the creation of purifying biotopes with species that help reduce the contamination levels of river water is sought. In communities without access to services, the proposal aims to use existing public parks and unused areas to create artificial wetlands, creating a water collection and purification network for later use. In the case of the WWTP Atarjea area, the proposal seeks to use these facilities as potential public areas in the area, incorporating them into the urban fabric and providing an aesthetic and social value of the water-sensitive approach. For this purpose, several water-sensitive tools are used: (3), (4), (5), (7), (10), (14), (15), (19), and (21).

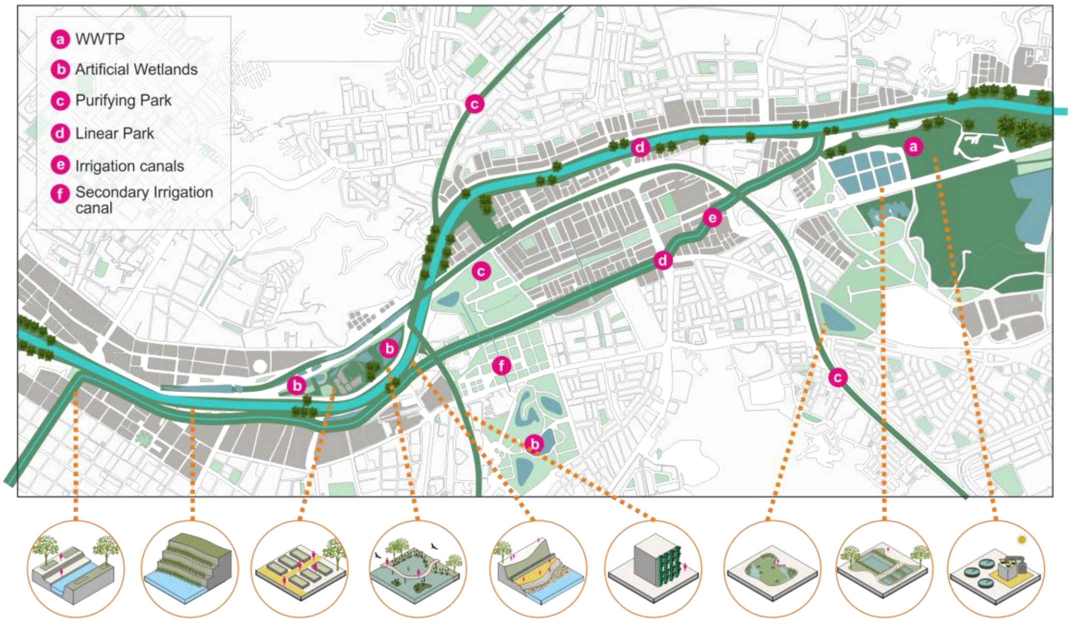


Figure 86: Masterplan - Rimac River area

Source: Created by author, 2021.

In addition to the water benefits, as shown in Figure 87, the proposal seeks to reduce the gap in access to public spaces and increase the number of green areas per inhabitant through the implementation of multifunctional terraces and green areas with low water consumption.

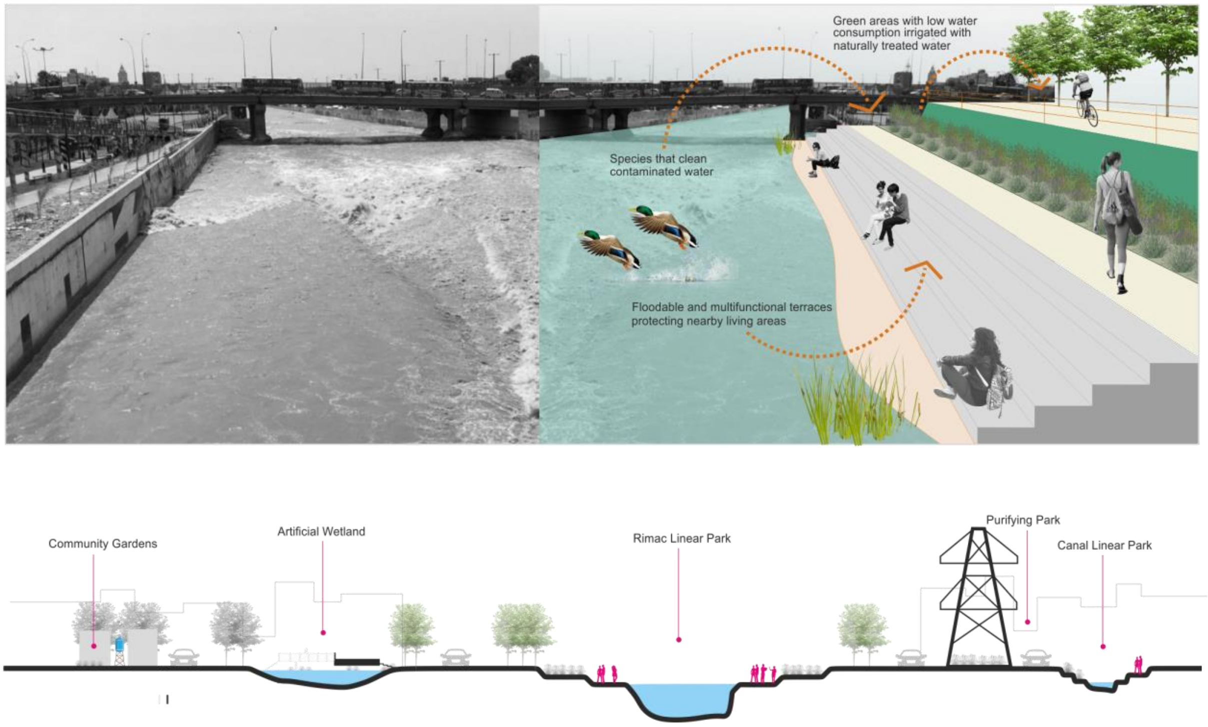


Figure 87: View and cross-section of the Rimac River proposal

Source: Created by author, adapted from Sovero, 2019, © EC-El Comercio

As shown in Figure 88, the intervention area could involve, through the management of the CHIRILU Council, several stakeholders from the civil society (users' association, Cantagallo community), from the private sector with a large number of companies and mainly from the public sector with representatives of more than four municipalities.

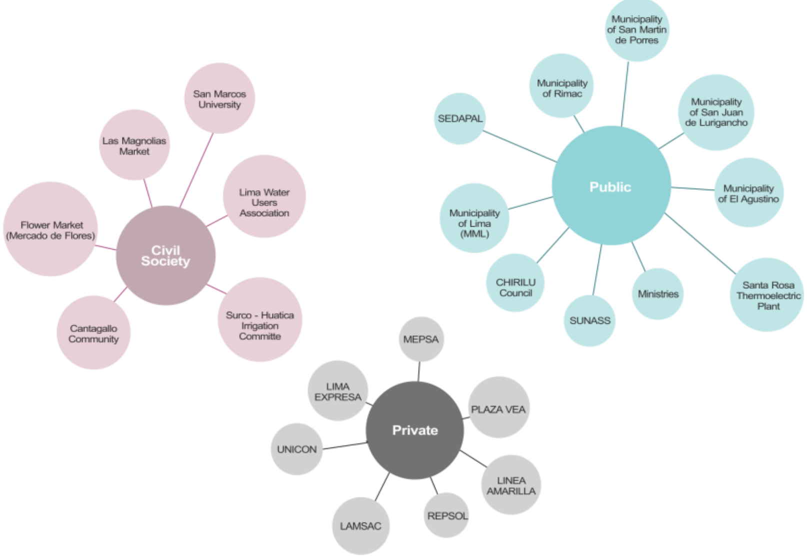


Figure 88: Potential Stakeholders of the Rimac River proposal

Source: Created by author, 2021.

5.4.3 Meso-scale: Restoring pre-Hispanic canals

The area selected for the development of the proposal, as shown in Figure 89, is an area between the districts of San Borja and Santiago de Surco where the Surco irrigation canal crosses. From the positive aspects, we can highlight the integration of the primary canal with secondary canals, the proximity to the municipal WWTP of San Borja, excellent connectivity, and the availability of local parks and multiple flat roofs to develop strategies. However, on the negative side, the lack of canal incorporation into the urban fabric, the irrigation of public green areas with potable water, and the high levels of per capita water consumption can be highlighted. Therefore, the main goal will be to EXPOSE and REUSE (4).

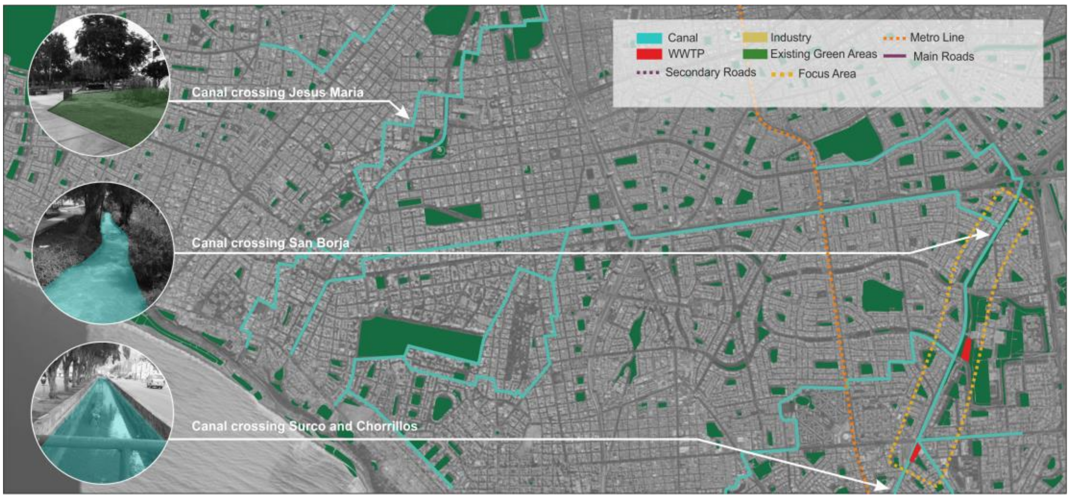


Figure 89: Characteristics and surroundings of the area of interest of the Surco canal

Source: Created by author, adapted from Zoom Earth, 2021.

As shown in Figure 90, the proposal aims to recover the network of pre-Hispanic irrigation canals by creating public spaces along their course. In addition, use the central berms of the main avenues to create a system of artificial wetlands to clean and reuse water for irrigation of public green areas. For this purpose, several water-sensitive tools are used: (4), (10), (11), (13), (27), (28), and (29).

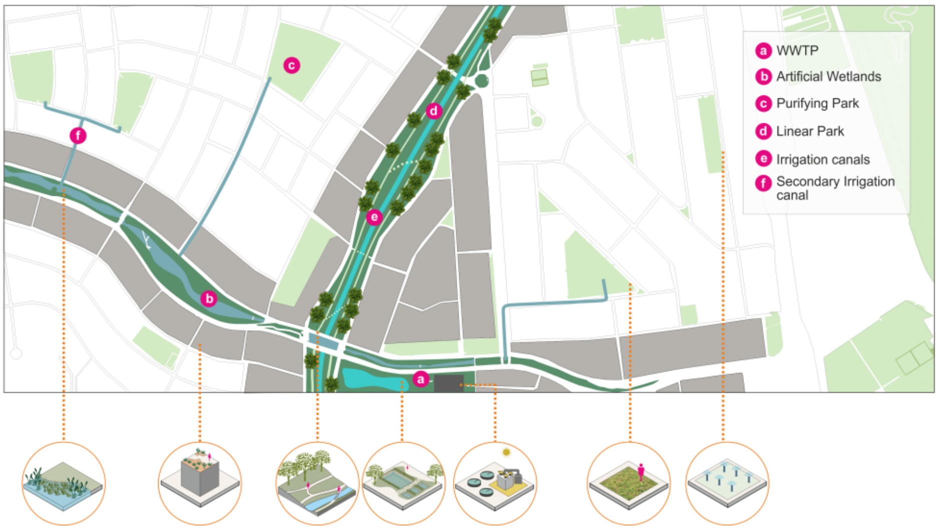


Figure 90: Masterplan – Surco irrigation canal area

Source: Created by author, 2021.

Additionally, in the case of the WWTP, the proposal seeks to incorporate the stabilization ponds as public areas, as shown in Figure 91, and create a sludge reuse system for the benefit of green areas. The change of high water consumption species (American grass) for cover crops such as aptenia and the incorporation of shade areas through planting trees will promote the reduction of heat islands. In residential areas, the creation of green roofs with xerophytic plants would also be beneficial.

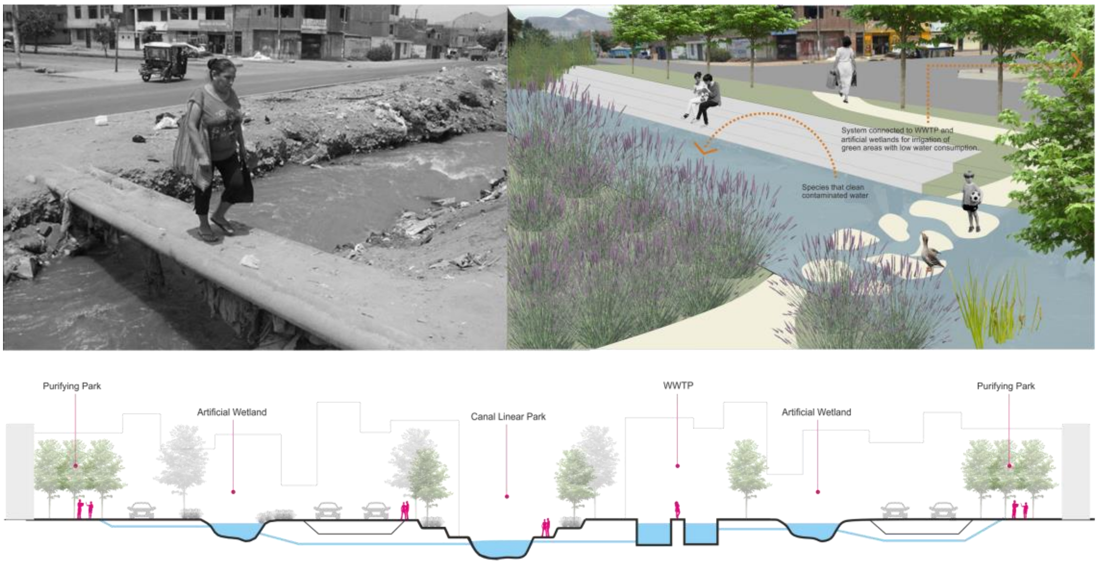


Figure 91: View and cross-section of Surco irrigation canal proposal

Source: Created by author, adapted from EC-El Comercio, 2014.

As shown in Figure 92, the intervention area could involve, through the management of the CHIRILU Council, several actors from civil society (users' association, neighbors of nearby urbanizations, Surco-Huatica irrigation committee), from the private sector, several local commercial companies, and mainly from the public sector with representatives of five municipalities, SEDAPAL and even the Armed Forces.

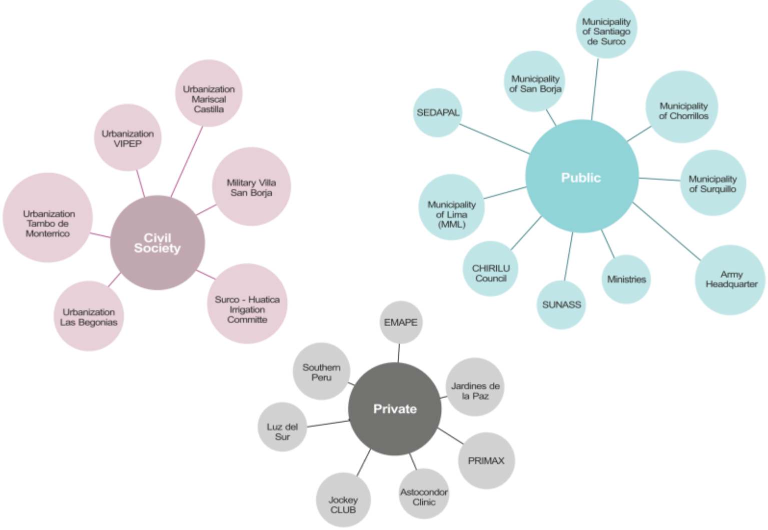


Figure 92: Potential Stakeholders of Surco irrigation canal proposal

Source: Created by author, 2021.

5.4.4 Micro-scale: Quebrada Verde - Bridging the gap

The area selected for the elaboration of the proposal, as shown in Figure 93, is an area on the left fringe of the Lurin Valley. Positive aspects include blue infrastructure (Lurin River) and WWTP Julio C. Tello near the community Quebrada Verde, fertile and permeable soils as it is an agricultural valley with high humidity levels in the upper part of the hills. On the negative side, however, there is a lack of water and sewage connections in the communities, pollution levels in the Lurin River, and the retreat of the coastal hills due to urban pressure and industry. Thus, the loss of important areas of biodiversity for the city. Therefore, the main goal will be to COLLECT and REUSE (1).

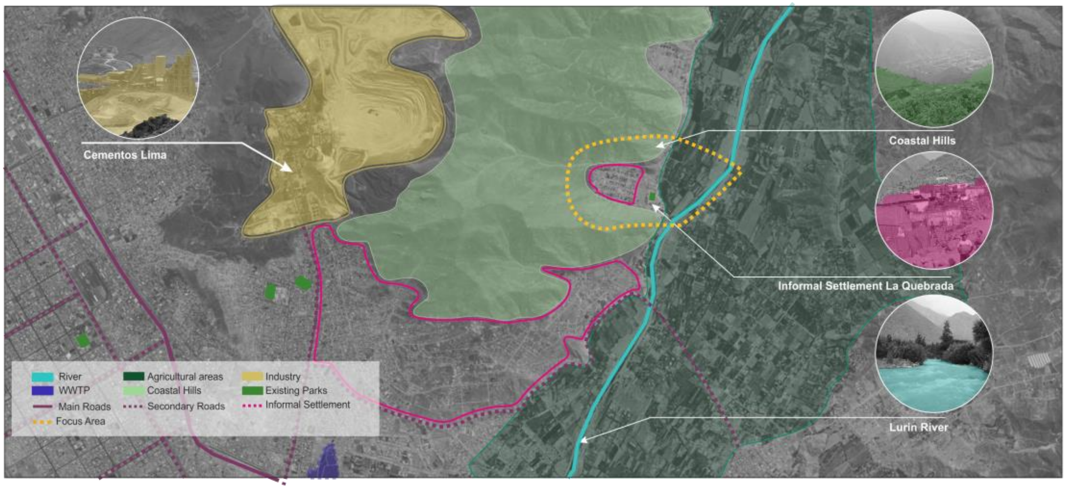


Figure 93: Characteristics and surroundings of the area of interest of Quebrada Verde

Source: Created by author, adapted from Zoom Earth, 2021.

As shown in Figure 94, the proposal's main objective is to close the gap in access to basic services, green areas, and quality public spaces in the peri-urban zone, using an interconnected network of fog collection systems, artificial wetlands, and linear parks. The latter is in order to protect the population and agricultural areas in case of flooding. For this purpose, several water-sensitive tools are used: (3), (5), (9), (14), (15), (16), (18), (19), (20), and (24).

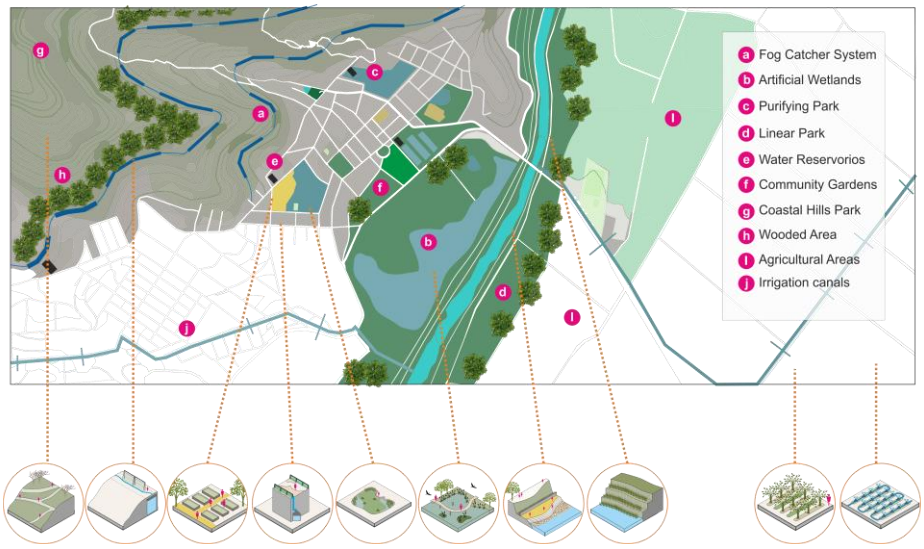


Figure 94: Masterplan – Quebrada Verde area

Source: Created by author, 2021.

In addition, as shown in Figure 95, to protect the hilly coastal areas, a system of slope parks should be created, taking advantage of the terraced areas to create communal gardens. In the upper areas, implementing a reforestation program to stop urban sprawl would also be beneficial. Given the high humidity levels, housing could also implement green roofs with residential scale fog catchers for non-consumptive uses.

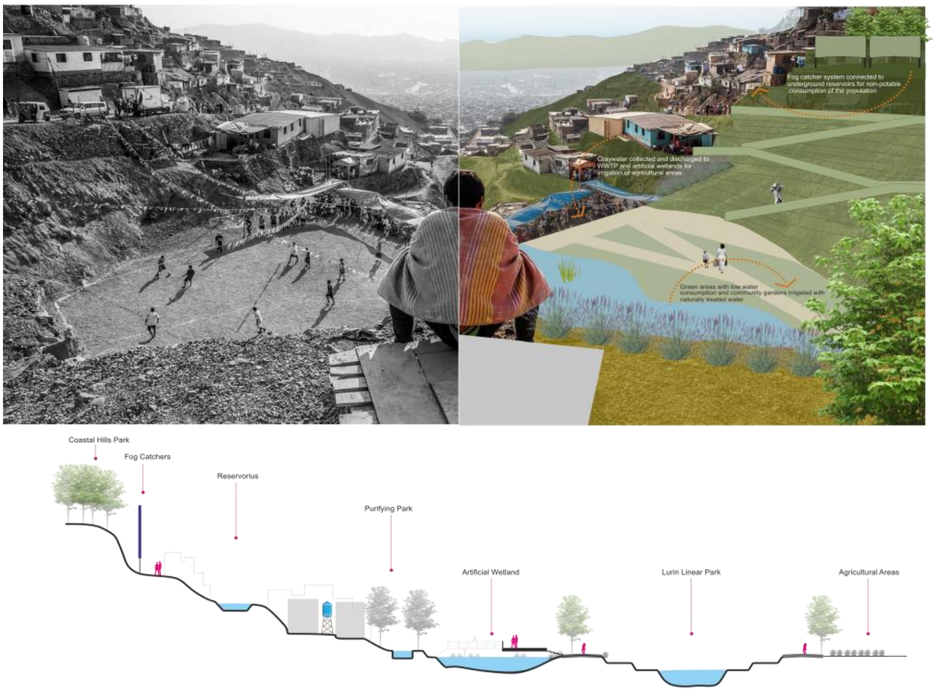


Figure 95: View and cross-section of the Quebrada Verde proposal

Source: Created by author, adapted from Facho, 2018, © Eleazar Cuadros.

As shown in Figure 96, the intervention area could involve, through the management of the CHIRILU Council, several civil society actors (users' association, Quebrada Verde community, Guayabo community, farmers' association), private sector companies such as Cementos Lima, and mainly the public sector with representatives of more than two municipalities, the Municipality of Lima, SEDAPAL and the Ministry of Agrarian Development and Irrigation (MINAGRI).

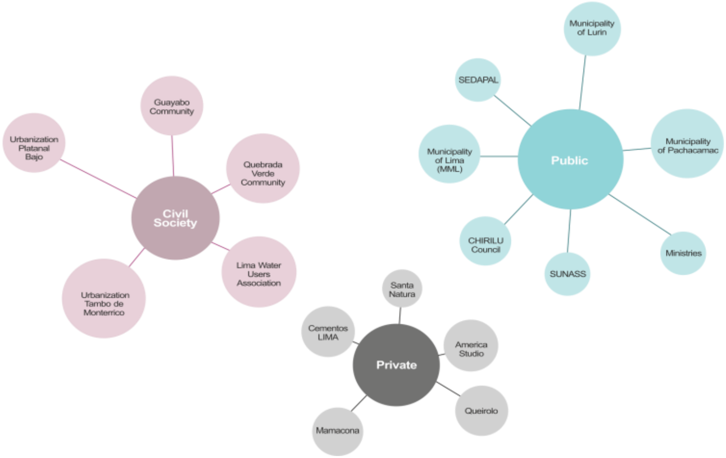


Figure 96: Potential Stakeholders of Quebrada Verde proposal

Source: Created by author, 2021.

Chapter 6: Policy Implications

This chapter will present the main implications for the correct management of the proposed vision and the central values of the research. A second part will suggest reference phases to move the vision from plan to action and a proposal for scaling up throughout the territory.

6.1 Implications

Lima is a megacity facing a water crisis impacting the city's population, production, and ecological environment. This situation is exacerbated by several interrelated factors such as rapid population growth, the impacts of climate change, weak governance, and inequity in access to services, which produce more adverse effects showing a bleak future for sustainability.

In order to address water scarcity and ensure water security, the research offers a holistic proposal articulating the integrated management of water, space, and ecological system, due to transforming the city into a supply basin, providing ecosystem services, promoting water-sensitive communities, and offering equitable access throughout the territory. The proposal does this through a shared vision for the future by providing adaptive solutions at various scales. The research is a contribution to planning Lima with water resources as a key element for sustainability. The introduction of a water-sensitive approach in the city also adds to the efforts to achieve the SDGs promoted by the United Nations.

Additionally, the research is a valuable contribution to the generation of patterns for the applicability of water-sensitive approaches in semi-arid environments and low rainfall levels and the transition to water-sensitive cities in developing contexts. From the technical aspect, the research contributes to the improvement and refinement of the UWMB method in developing contexts, given the limited supply of applied cases. However, several aspects of the current governance system and public policies need to be modified to overcome the challenges to achieve the vision within the established timeframe and transition Lima to a water sensitive city:

6.1.1 The deployment of water sensitivity strategies requires multi-level governance

The shift from traditional or centralized management, highly influenced by 20th-century solutions, to decentralized water management by diversifying water sources also implies moving from top-down and centralized governance models characterized by institutional fragmentation to a collaborative multi-level governance system (Wong, Rogers, and Brown, 2020). In the Peruvian context, one of the main reasons for a worn-out consonance between ministries is perhaps the weak performance of the National Water Authority (ANA). The country's water management needs to ensure that all government structures and stakeholders respond to clear and specific functions by strengthening ANA's multisectoral role. As stated by Beza and colleagues, a cross-cutting level is ideal for inserting through it WSUD policies and standards, thus fostering rapid adoption at all scales at the national level and promoting positive environmental outcomes uniformly across the territory (Beza, Zeunert, and Hanson, 2018). To this end, key actions such as their secondment from any ministry and the establishment of intergovernmental agreements under their leadership where all stakeholders establish and monitor commitments made to achieve the common goal, as seen in Australia with the National Water Initiative, are of vital importance. Other urgent actions are to frame water-related policies through a preventive strategy in the face of climate change and seek to minimize the impacts of natural disasters of which the Peruvian reality and with special attention, Metropolitan Lima is not exempt. Today, as demonstrated by The Netherlands with the Delta Plan, it is not enough to protect; long-term solutions must be sought in harmony with the environment to ensure the water security of the population and respond to climate change in a resilient manner (OECD, 2014).

In the context of Lima, water management at the basin level requires addressing the problems of water scarcity and high levels of pollution of the tributaries that compose it collectively through shared plans and tools that bring together concrete actions and responsibilities of each member, whether public, private, or civil society. Another crucial action at the basin scale is the collection and exchange, through the Observatory of the CHIRILU Council, of relevant water information and data from all the stakeholders involved, which would mean better quality, updated, and easily accessible data that would benefit a more sustained and transparent decision making.

Regarding the lack of technical capacity and existing diagnostic tools at the basin scale (and at the national level), as stated by Wong, this is one of the significant obstacles to applying a water-sensitive approach (Wong, Rogers, and Brown, 2020). Cases such as The Netherlands show that for an effective response to water challenges, the commitment to innovation and new and better technologies is the key, being necessary to establish a strong link between the public, private, and research sectors to strengthen the technical and human capacity of professionals in the country (OECD, 2014). Therefore, the CHIRILU Council can play a fundamental role as an articulating entity between public-private actors and the education sector through the Water Availability Development Plan (PADH) working group, whose objective is to plan and coordinate the sustainable use of water in the interregional basin. This alliance should be used to develop multisectoral training programs (engineering, sanitation, environment, and governance) and create a project portfolio full of multidisciplinary perspectives, promoting the sharing of knowledge and experiences. This exchange is the basis for developing effective policies, implementing the most appropriate solutions, and ensuring projects' construction, operation, and maintenance (OECD, 2021a).

6.1.2 The deployment of water sensitivity strategies requires spatial cohesion

Water management requires an adaptation between administrative and basin level boundaries, which must be addressed at a multisectoral level and led and articulated by the National Water Authority. From the ecological aspect, projects such as Room for the River in The Netherlands and wetlands in Australia on a smaller scale demonstrate how a complete understanding of the water cycle can establish a better relationship between water and space and promote living spaces and biodiversity. Indeed, in the case of Lima, living areas (coastal hills and wetlands) and agricultural valleys have been drastically reduced throughout history, and even today, they coexist under constant pressure in the face of formal and informal urban expansion processes in the city. In that sense, it is necessary to develop conservation and sustainability strategies, generating added value for the population. Although the Municipality has incorporated regulations for their protection at the local level, the truth is that it requires an articulation between the Urban Planning Plan of the city (Lima), the region (CHIRILU), and the Water Resources Management Plan. Therefore, the Working Group on Natural Infrastructure and Water Conservation of the Chillon Rimac and Lurin basins (INCA) can play an important role. In addition, an adaptation of the public investment system is required at all scales, with particular emphasis on the municipal scale. This aspect is mainly because currently, they are framed in traditional systems that only aim to build towards Blue and Green Infrastructure (BGI) approaches that seek to conserve and rescue the historical value of the land, leaving aside environmental aspects. This aspect will also encourage reducing the gaps of green areas per capita and public spaces, today distributed heterogeneously throughout the city, strengthening the social development of citizens.

6.1.3 The deployment of water sensitivity strategies requires robust monitoring and recycling systems

Conserving water quality is vital to ensure the availability of the resource. Cases such as The Netherlands show how the articulation between monitoring water quality and securing freshwater sources for the population, agriculture, and industry requires regulation by a cross-cutting entity, such as the Water Authority. In addition, through initiatives such as Polluter Pays, the water management system imposes taxes in the form of emission taxes, calculating their rates based on pollution indices according to the user category: pollution tax for households or companies, as well as wastewater treatment tax. While the primary function of taxation is to reduce general pollution and protect the cleanliness of the water, it also allows the creation of sufficient funds for the implementation of investment and maintenance projects on a regional scale regulated by the Water Authority (Van Steen and Pellenbarg, 2004). Although ECAs and LMPs were created as tools that seek to control quality standards in the Peruvian context, the truth is that the city does not have a comprehensive and permanent system for monitoring and evaluating water quality. It is necessary to establish the regulatory functions of a specific entity, for example, the Basin Commissions. This designation of functions could also benefit the financial independence of the Council and increase its capacity to execute strategic projects throughout the basin to strengthen the headwaters and revitalize the riverbanks.

On the other hand, the transition to a water-sensitive city implies the need to diversify water sources to maximize the resource's availability, especially in environments where climatic and geographic aspects make water scarcity a natural occurrence. In the local case, Lima has a strong dependence on centralized systems. The UWMB results show that the source with the most significant potential to diversify to increase the city's water availability in the face of the crisis is wastewater. Although treatment has risen significantly in Lima in recent years, there are still deficiencies in the system that need to be addressed. In practice, shortcomings in terms of installed technologies and infrastructure maintenance reduce the actual production capacity of Lima's wastewater treatment plants. The high level of pretreatment and primary treatment reflects the need for technological updating, requiring knowledge transfer, capacity building through a process of education and training, and investment in research to reduce the existing gap. From the management point of view, although a series of strategies have been established within the framework of Water Resources Management, the truth is that it is necessary to implement normative elements that regulate the reuse of wastewater, giving priority to drinking water consumption. Furthermore, in this context, a regulatory framework is required to promote and regulate the adequacy of the required treatments based on pollutants and future water use, as is the case in Australia (Department of Planning and Local Government, 2009). The use of water without prior treatment should also be effectively sanctioned, as in agricultural areas and peri-urban informal settlements.

At the municipal level, where most secondary and tertiary treatment plants are concentrated, it is necessary to create a system of financial incentives together with private actors to promote and increase the irrigation of public green areas through the reuse of wastewater. In the case of by-products generated (sludge), a normative and regulatory framework is required to reuse sludge nutrients that can be converted into fertilizers or reused for energy generation, allowing the city to stop depending on hydroelectric energy that today satisfies the population's demand. According to the sludge reuse model in New Haven Village (Adelaide), it could even be transformed into bricks for construction.

6.1.4 The deployment of water sensitivity strategies requires participatory systems

Participation is crucial when discussing water-sensitive strategies and integrated water resources management at the management and community levels. At the management level, promising progress has been made in the local context with creating the CHIRILU Basin Council. However, there is still a lack of balanced participation, especially for civil society actors and municipalities in the upper watersheds. Opening the Working Groups in the Council to urban planners, urban specialists, and final-users instead of just water stakeholders could significantly increase efficiency through collaborative work. Therefore, this will allow an alignment of goals and expectations at the level of strategy design and during implementation and subsequent maintenance and monitoring of projects.

From the community aspect, the comparison between cases such as The Netherlands, Singapore, and Belgium show that even when multilevel governance is usually top-down, it is required not only to inform and collaborate indirectly but to bridge participation gaps by actively involving end-users and the local population, understanding that the top-down approach can only work successfully if combined with a bottom-up one. Recognizing local power is vital, as highlighted by Radcliffe and Beza, at the local (micro) scale, it is sometimes more feasible and cost-effective to ensure better functioning of water-sensitive strategies (Beza, Zeunert, and Hanson, 2018; Radcliffe and Page, 2020). This aspect is primarily in the face of diversified sources stigmatized by the population, such as wastewater reuse for non-potable and potable consumption, where a close relationship and constant communication are vital (Radcliffe and Page, 2020). In this sense, in the local case, the incorporation of participatory processes in water-sensitive strategies and committed educational programs should be a requirement both at the neighborhood and watershed scale, as well as the recognition of grassroots social organizations (Vasos de Leche and Community Kitchens in informal settlements, Neighborhood Councils in urbanized areas and Farmers' Association in rural areas) as agents of change. The creation of Urban Laboratories in front of each project promoted by the CHIRILU Council in alliance with municipal governments is a good platform for collaborative work with stakeholders (public and private actors) and the population seeking a better understanding of the water cycle and strong involvement of end-users and local citizens in decision making (BRIGAID, 2020). In the case of strategies involving wastewater reuse, incorporating Urban Laboratories of professional endorsements from the health field and education for informing water quality conditions is vital. In addition, incorporating sensitization and awareness programs relying on grassroots social organizations and educational entities would help regulate daily per capita consumption and deepen the repercussions of individual actions in the context of a water crisis.

6.1.5 The deployment of water sensitivity strategies requires sustainable financing

The principles of the water-sensitive approach frame the need to establish collaborative, long-term, and flexible economic sustainability mechanisms; however, to promote public-private sector investment, there is an urgency to develop an economic valuation of tangible and intangible benefits (Wong, Rogers and Brown, 2020).

The experience in The Netherlands shows the need for a rapprochement with the private sector, which is one of the keys to the development of a multilevel model. In the context of

Lima, it is necessary to take advantage of the concentration of a large part of GDP in the city and to build bridges with the private sector through attractive fiscal incentives for private enterprise in order to increase the quantity and quality of water in the CHIRILU basin and to cover the gap in access to essential services in areas that are still vulnerable. However, to allow the development of projects by the private sector, it is necessary to correctly value water resources, which is why tariff regulation and the correct management of economic sanctions in case of non-compliance with the norms are required.

6.2 Systemic Transition: Phasing

The phasing indicates the order of the central spatial and public management interventions concerning the vision proposed in Chapter 5. As mentioned above and shown in Figure 97, the basis of the proposal is a combination of top-down and bottom-up approaches. In that sense, and given the priority of closing the gap in access to essential services in peri-urban areas of Lima, the micro-scale project is the first in the line of work. However, for this to succeed, local governments need to initiate strategic changes to support the intervention.

The project in the community of Quebrada Verde begins with the generation of urban laboratories to elaborate a participatory diagnosis and design document. At the same time, from the public management point of view, the formalization of the Vision through the strengthening of the CHIRILU Council and the articulation with other actors of the society, both from the private and civil society, must take place. Once the foundations have been laid, the project moves to the second stage of implementation and maintenance.

Once this project has been developed, it is necessary to implement an evaluation and monitoring system that will allow it to be replicated in other city sectors. At the same time, the second meso-scale project is initiated, and finally, in a third stage, the macro-scale project, given the scale of the intervention.

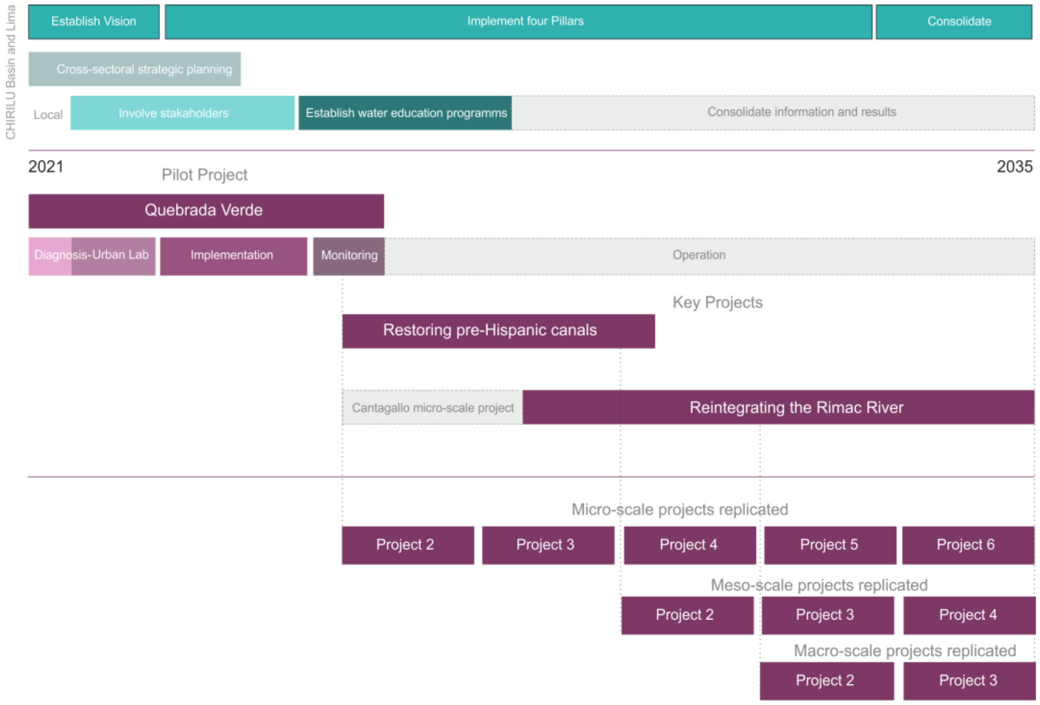


Figure 97: Phasing

Source: Created by author, 2021.

6.3 Upscaling

The proposals presented in Chapter 5, once a more solid public policy base is in place, can be replicated and scaled up to other areas of the city of Lima, as shown in Figure 98. Thus, in the case of macro-scale interventions, they could be implemented along the edges of the Chillon and Lurin rivers after a process of adaptation. In the case of the mesoscale intervention, it could be adapted and implemented in other flat and urbanized areas of the central city. The strategy presented at the micro-scale would require further adaptation since the soil conditions of informal zones are not homogeneous throughout the city. There are informal settlements in flat areas in Lima, although certainly to a lesser extent than in hillside areas. There are also areas in the city that do not require a comprehensive intervention but could adopt specific strategies from the catalog. It should be mentioned that this proposal is purely referential since, as previously mentioned, further study is required for a better result.

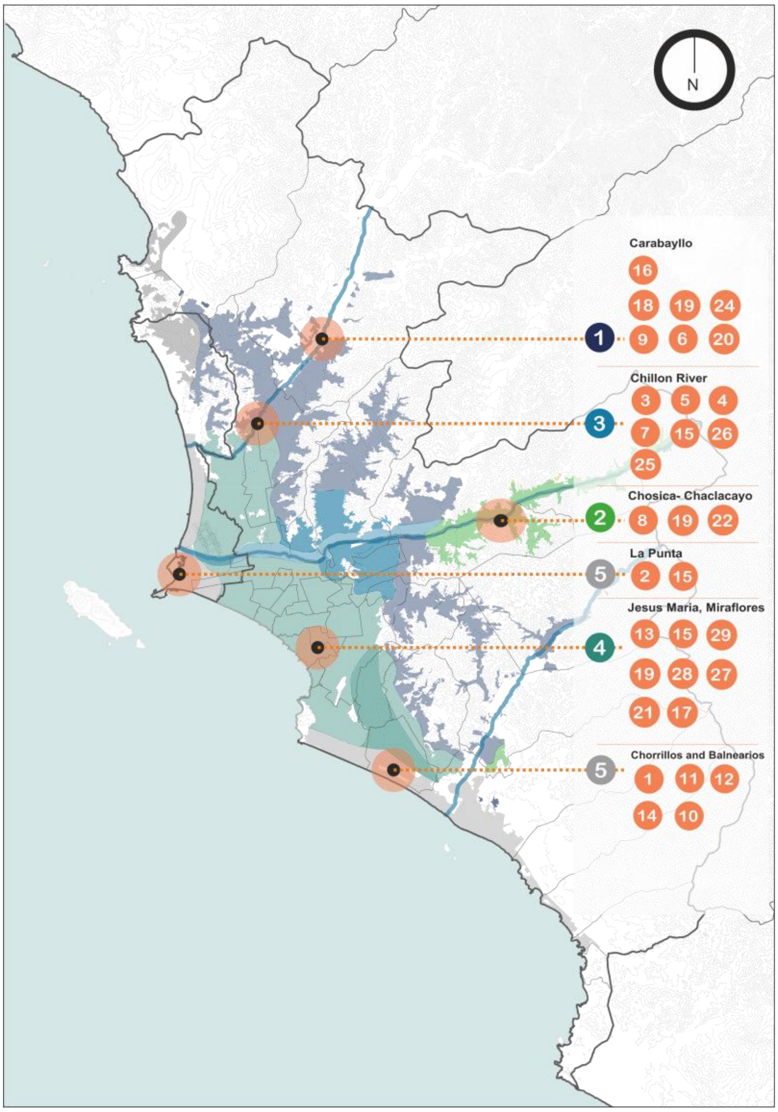


Figure 98: Upscaling the Vision

Source: Created by author, 2021.

Chapter 7: Conclusions and Recommendations

7.1 Summary of findings

Throughout the introduction, eight questions were formulated to provide a solid basis for the research. The conclusions summarize the most important findings and encompass the answers to the proposed questions. The first sub-question identifies the key elements of a water-sensitive approach in semi-arid contexts. The literature review on essential concepts reveals that given the current need to cope with climate change and increasing urbanization, the Water Sensitive City (WSC) is a vision for the future that seeks to transition from a state of traditional and ineffective water management systems to a state of sustainability. To ensure success in the face of the multiple challenges that the transition faced, the literature review highlights the importance of employing a holistic and adaptive approach to various environments such as that offered by WSUD. However, the findings also emphasize that the transition process is designed and idealized for developed contexts insofar as their social and economic stability allows them to think and create strategies for the future, contrary to what happens in developing environments where the levels of complexity are higher.

Similarly, in the water-sensitive approach, its application still tends to focus on rainwater management. However, it should be noted that in the case of semi-arid environments, there is a need for a better understanding of the water cycle and to focus on tools that improve thermal comfort and sustainable irrigation systems in order to preserve green spaces. In the line of environments with low precipitation levels, the literature review also highlights the benefits of implementing hybrid water management systems to better respond to climate change's uncertainty and decrease water sources. Another relevant aspect of the findings is the fundamental role of ecological infrastructure in the urban water cycle balance by providing ecosystemic benefits, which is why it needs to be taken into account to promote the effectiveness of a water-sensitive strategy in semi-arid environments. In this need for a better understanding of the urban water cycle, the findings show tools such as UWMB to be promising in analyzing the metabolic processes of the natural and artificial sources that compose the water system of an urban environment. However, it still requires further research to be more consistent and less presumptive in developing contexts.

Throughout the third chapter, the literature review analyzes best practices transitioning to a WSC and applying water-sensitive strategies to answer the second research sub-question that seeks to draw lessons from the challenges of implementing multilevel governance models and intervening in semi-arid environments. The evidence reveals that given the challenges facing urban environments today, it is necessary to generate a close link between all actors in society. It is also emphasized that decentralized governance should be applied by linking all territory scales, defining roles and responsibilities in each to achieve a shared vision for the future. The findings establish the need to bridge spatial, regulatory, technical, and economic gaps that, together with the capacity to have flexible, supportive and sustainable institutions, and the involvement of end-users and the community in decision-making, ensure the system's success. On the other hand, the literature review also shows that in semi-arid environments, the focus is on meeting irrigation water demands through wastewater reuse and taking advantage of the aesthetic and ecological benefits that tools such as artificial wetlands offer compared to traditional systems. The findings also recognize the potential of applying micro-scale projects to provide greater social returns and ease of building community confidence in stigmatized recycled water. However, the results also highlight that the applicability and potential success of the models imply having basic needs covered and a more stable base that allows taking the following steps. This aspect is not characteristic of developing environments, as its adoption is still limited and theoretical.

Throughout the fourth chapter, the analysis of the case study seeks a greater understanding of the inherent characteristics of Metropolitan Lima, which also encompasses a series of four specific sub-questions. Thus, the third sub-question aims to identify and analyze the ecological infrastructure that makes up the case study. The results show the critical role of blue and green infrastructure, both natural and artificial, in Lima's landscape and highlight its capacity to adapt to the natural conditions of the environment. In green infrastructure, the results show the benefits of the coastal hills, which are a natural habitat for endemic species; likewise, the valleys provide productive benefits to the city. In blue infrastructure, rivers are the primary source of water supply for the urban environment, while wetlands are a source of biodiversity and spaces that promote the natural purification of pollutants. However, the findings also highlight their vulnerability to rapid urban growth, the loss of areas in hills and valleys, and the contamination of blue elements puts the stability of the urban water cycle at risk, reducing the city's resilience. In the case of artificial green infrastructure, the findings show the deficit of green areas and public spaces per capita with particular intensity in the peri-urban areas of Lima.

The fourth sub-question seeks to identify the current limitations and opportunities presented by the governance system. The findings show the existence at the national level of a consolidated regulatory framework emphasizing multisectoral cohesion by introducing the Integrated Water Resources Management (IWRM) approach as the central axis. However, in practice, its application is limited. The ministries pursue particular objectives in the face of the inability of the main governing body in integrated water resources management to articulate unified policies. At the basin scale, creating a Council is seen as a promising step forward. However, it faces institutional fragmentation and conflict of interests over water use on its stakeholders. The findings also highlight the mismatch between the hydrographic and administrative boundaries. This situation creates confusion and duplicates roles or responsibilities among the actors that comprise the basin of which Lima is a part. Thus, the fifth sub-question attempts to analyze the urban metabolism to understand better the urban water cycle in Lima and identify the sources with the most significant potential in the face of the need to diversify.

After applying the Urban Water Mass Balance (UWMB) method, the results show that Lima's water demand depends almost entirely on a centralized system and significant losses in water supply due to leaks or unregistered connections. The results also suggest the potential of wastewater to increase water availability in the city; however, the findings also show that quantitatively it fails to meet the entire demand and needs to be integrated with other sources. However, the findings highlight the need to increase secondary and tertiary treatments in existing wastewater treatment plants (WWTPs) to increase their potential as an alternative source.

Towards the end of the chapter, with the picture of Lima clearer, the sixth sub-question focuses on identifying the main drivers of water scarcity in the city. The analysis reveals that in Lima's current water scarcity scenario, the main interrelated factors are rapid population growth, climate change impacts, weak governance, and inequity in access to services that exacerbate the crisis. However, it also highlights a cause-effect relationship in that these factors together produce more adverse effects and, if not addressed, will lead to even more significant problems.

Throughout the fifth chapter, a holistic water-sensitive vision for Lima is designed to answer the seventh research sub-question that seeks to establish strategies for a better transition to a Water Sensitive City (WSC). The vision is created as a unifying future state with a 15-year horizon addressing all the city's water availability challenges. A sustainable, balanced water and ecological system in Lima by 2035 seeks to facilitate Lima's transition by restoring the balance of the water and ecological cycle in Lima and at the level of the CHIRILU basin given its territorial and hydrological dependence. Finally, towards the end of the chapter, key projects are proposed to answer the eighth sub-question of the research, which seeks to establish a methodology to adapt the strategy to different scales within the city. Thus, based on an understanding of the city and an overlay of layers such as water structures, ecological infrastructure (natural and anthropogenic), urban composition, and geographic conditions, five goals are established: (1) Collect and Reuse, (2) Delay and Drive, (3) Treat and Reuse, (4) Expose and Reuse, and (5) Protect and Clean. A catalog of adaptive spatial proposals at macro, meso, and micro-scales is developed.

Various aspects of the governance and public policy system must be modified to overcome the current challenges if the vision is to be achieved within the timeframe and Lima is to transition to a water-sensitive city. Thus, the seventh chapter outlines some implications that should be considered, such as the basis for developing a multilevel governance system, incorporating spatial cohesion, promoting monitoring systems and encouraging wastewater recycling, improving stakeholder participation, and developing sustainable financing.

How could Lima successfully transition to a water-sensitive development?

In summary, the findings provide sufficient support to answer the main research question: How could Lima successfully transition to a water-sensitive development? The available water resources of Lima, the second-largest city in the world located in the middle of a desert, are not sufficient to meet the city's demand and the contamination of its water sources further reduces its capacity to act. The city's water crisis is exacerbated by several interrelated factors such as rapid population growth, climate change impacts, weak governance, and inequity in access to services, all of which have further adverse effects on Lima's population, production, and ecological environment. Implementing a holistic water-sensitive approach to transition the city towards sustainability is a solution to address water scarcity and ensure water security. This vision implies transforming the city into a supply basin by diversifying its sources through the potential shown by wastewater, the recovery of water wasted in leaks, humidity, and adapting to the inherent constraints of a semi-arid context. It also contemplates offering ecosystem services by preserving the ecological infrastructure and bringing it into equitable cohesion with the urban environment and promoting sensitive communities by establishing multilevel management systems at the functional and territorial levels and involving the end-user and communities in decision making. However, unlike in a developed environment, these transformations are not sufficient to ensure the success of the city's transition.

The findings in Lima confirm that while the flat and urbanized areas are seen as Drainage Cities, on the contrary, the informal areas present a level similar to that of a Water Supply City. This aspect implies different levels of progress between each space, which essentially translates into dissimilar water needs. As such, ensuring the transition to a Water Sensitive City (WSC) requires first recognizing the specific gaps that need to be bridged in each city environment. This understanding involves localized strategies in both the Drained City and the Water Supply City during the first stage of the transition. Once the existing inequity in access to water and ecosystem benefits is addressed, the city can leap to the next stage of development.

7.2 Suggestions for Further Research

Meeting the city's challenging water demands is a complex task indeed. The research makes a serious attempt to offer a holistic perspective to make Lima's transition to a Water Sensitive City feasible, serving as a basis for an even more comprehensive and effective strategy in the future. However, to better understand the implications of this, a series of recommendations could be taken into account:

1. The water-sensitive framework developed throughout the research has been drawn substantially from the study and analysis of programs and strategies applied in developed countries with much higher rainfall levels than those shown in Lima. Further research on case studies in developing countries and arid or semi-arid environments would be of vital importance to expand knowledge on the adaptability of the water-sensitive approach in contexts with more significant socioeconomic, climatic, and geomorphological challenges.
2. On the other hand, the application of the urban water mass balance assessment method in Metropolitan Lima was formulated by defining the system boundaries based on the territorial organization of the city. However, applying the equation at the watershed scale and even at the micro-scale in future research could be beneficial for a better understanding of the water cycle for the city and even extrapolate its usefulness by serving as a basis for analyzing water cycles in semi-arid environments with similar characteristics.
3. The improvement strategies presented throughout the research aim to shorten the water supply and sanitation gap in peri-urban areas and fill the irrigation deficiencies in urban vegetable areas of the city by highlighting the importance of wastewater recycling through artificial wetlands and fog water harvesting. However, in wastewater reuse, more research from the social sphere on the perception and rejection of wastewater reuse for non-potable and potable consumption is needed, and appropriate strategies to increase confidence in the population. From the public health aspect, more research is needed on scientific evidence that disproves or demonstrates the dangers associated with mosquitoes and microorganisms to people's health; this knowledge will allow future solutions to address the problem.
4. The high levels of humidity concentration in the hillside areas of the city produce fog during long periods of the year, promoting its transformation in the not too distant future into an essential alternative water source in Lima. However, to affirm this, further research concerning its benefits, collection methods, and quantitative measurement systems, as well as its economic viability, would be required.

The suggestions, in essence, would entail further research to include a more detailed analysis allowing for a more robust holistic framework and therefore closer to real solutions.

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