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A WATER ALLOCATION INDICATOR FOR HYDROGRAPHIC BASINS

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MEMORIA PARA OPTAR AL TÍTULO DE INGENIERA CIVIL QUÍMICA

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RESUMEN DE LA TESIS PARA OPTAR AL GRADO
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RESUMEN DE LA MEMORIA PARA OPTAR AL
TÍTULO DE: Ingeniera Civil Química
POR: Francisca Javiera Andonie Bahamondes
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INDICADOR DE ASIGNACIÓN DE AGUA PARA CUENCAS HIDROGRÁFICAS

El agua es fundamental para el desarrollo de la vida y el medio ambiente, por lo que su estrés y escasez son graves problemas a nivel mundial. Chile se encuentra entre los treinta países con mayor riesgo hídrico. Debido a lo anterior, cada vez es más necesario resolver el problema de asignación del recurso hídrico y a su vez, tener un concepto más amplio para su protección. Este trabajo crea un indicador vectorial de asignación del agua (VWAI), que evalúa qué tan equitativa es la asignación en una cuenca. El indicador se pone a prueba en un caso real, analizando la situación actual y futura mediante un problema de optimización.

El primer paso del trabajo consiste en definir un Sistema de Contabilidad del Agua (WAS) para los principales usos del agua en Chile. Se definen ocho usos, clasificados en consuntivos y no consuntivos. El WAS tiene tres categorías: usos consuntivos, usos no consuntivos y contaminación de ambos usos. La primera determina cuánto es el suministro de agua para una actividad específica, la segunda cuantifica el agua comprometida por el proceso, y la última la contaminación causada por cada uso. La definición de VWAI depende de dos WAS: uno que representa un contexto ideal y otro representa el contexto real de la cuenca.

El indicador vectorial es una comparación, por medio de la desviación estándar, que muestra el estado de la cuenca en cuanto a las necesidades de agua y la contaminación provocada por los usos. Esta estructura permite dimensionar la distancia en qué se encuentra el contexto actual del deseado, facilitando la toma de decisiones a las entidades. El indicador cuenta con tres dimensiones: a) usos consuntivos, donde la evaluación está en el cumplimiento de la demanda, determinando si un uso está desabastecido o sobreabastecido; b) usos no consuntivos, donde la evaluación está en la diferencia de necesidades de agua según lo que se requiere y lo que se utiliza; y c) la determinación de la contaminación para cada uso en ambos casos. Se evalúa en cuánto, el caso actual, ha reducido la contaminación respecto a un caso base.

La Organización de las Naciones Unidas para la Agricultura y la Alimentación (FAO) desarrolló el concepto de tenencia de agua para referirse a la asignación en lugar de derechos de agua. Dicho concepto es más completo debido a que considera y determina cómo la sociedad se relaciona con el agua y los recursos naturales. Este trabajo analiza los resultados del indicador y cómo se puede mejorar la asignación desde una perspectiva de tenencia de agua, con el objetivo de protegerla y preservarla. El indicador muestra dónde predominan los problemas de asignación y funciona como base para analizar las consecuencias sociales, económicas y ambientales, y las ventajas y desventajas de la asignación. Por último, se presentan recomendaciones para globalizar el indicador y adaptar su uso a cualquier país, así como los aspectos a mejorar para una mejor caracterización del estado de cuenca.

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A WATER ALLOCATION INDICATOR FOR HYDROGRAPHIC BASINS

Water is fundamental to the development of life and the environment, becoming its stress and scarcity severe problems worldwide. Chile is among the top thirty countries under hydric risk. Based on the global and country situation, there is a need to solve the hydric resource allocation problem and to have a broader concept of protecting the resource. This work creates a vectorial water allocation indicator (VWAI), which assesses how much the hydric resource allocation in a basin is fair or equitable. The indicator is tested in a case study to assess the current situation and how it can be improved through an optimization problem.

The first step is to define a Water Accounting System (WAS) for the main water uses in Chile. Eight uses are defined and classified into consumptive and non-consumptive use. The WAS comprises three categories: consumptive uses, non-consumptive uses, and pollution of both uses. The first determines the water supply for a specific activity, the second quantifies how much water is used in the process, and the last determines the water pollution caused by each use. The VWAI definition depends on two WAS: one indicates an ideal context, and the another indicates the current context.

The vectorial indicator is a comparison through the deviation, which aims to show the basin state regarding the water requirements and contamination caused. This structure allows the assessment and gauging of how close or far the current context is from the desired one, facilitating decision-making for involved entities. The indicator is three-dimensional, and its components are the same as for the WAS: a) consumptive uses, in which the evaluation is about the demand fulfillment, determining if a use is under-supplied or over-supplied; b) non-consumptive uses, in which the evaluation is about the water requirements difference; and finally, c) it assessment of the pollution caused in both uses. The assessment is about how much the current case has reduced the pollution regarding a base case (previous year).

The Food and Agriculture Organization developed the concept of water tenure to refer to a water assignment instead of rights. The tenure concept is more general than the water rights concept by including the understanding and determining of how society relates to water and natural resources. This work analyzes the indicator results and how they can improve the allocation with a water tenure perspective, aiming to protect and preserve the water resource. The indicator shows where the allocation issues prevail and works as a base for analyzing water allocation, the social, economic, and environmental consequences, and the advantages and disadvantages of the allocation. Finally, this thesis presents recommendations to improve the indicator, have a better basin status approach, and globalize it to make it adaptable to any country.

A todos y todas las personas que creen que el
cambio aún es posible y luchan por un futuro más
sustentable, donde se respete a los animales y
al medio ambiente como corresponde.

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Chapter 1

Introduction

This Section gives a general background about the water problems in the country and the world. Besides, it introduces natural resource accounting and defines how the countries allocate water based on their governance forms and legal frameworks. Finally, this chapter analyzes the national scenario and its problems regarding water resources.

1.1. Climate Change and Water

The current climate crisis occurring at a global scale affects necessary resources for the development of ecosystems, and human societies, including water [1]. Water is necessary to maintain human life and development because it is a fundamental resource for the main socio-economic sectors for drinking, hygiene, food, energy production, economy, and ecosystem care [2]. Therefore, the study of water is becoming essential for its care and protection.

Research indicates how the relationship between climate change, water resources, and the hydrologic cycle has become and will continue to become more complex, affecting the human population. Climate change researchers estimate an increase in global water scarcity by approximately 20% in this century [3], and demographic growth and economic development increasingly contribute to the lack of water and its contamination. Projections indicate that in the midst of the 21st century, between 2,000 million and 7,000 million people will live in water scarcity conditions [3].

All the components of the hydrologic cycle have remarkable natural variability. Nevertheless, temperature increases have affected hydrologic cycles and system variation in recent decades. Precipitations have demonstrated high variations, and several studies expect to continue this behavior [4]. The snow cover has also been decreasing, glaciers have increasingly melted, water vapor content has been increasing in the atmosphere, soil moisture and runoff have changed, and contaminants and water temperature have increased [3, 4]. Consequently, the weather expects extreme events, such as increasing floods, droughts, mudslides, typhoons, cyclones, diminution in river flow, and worse water quality [3].

Water stress and scarcity have become severe problems in various parts of the world because freshwater has two principal functions: it is a prerequisite for life, and a commodity and an economic resource [5]. In fact, the global population will be around 8.9 billion people by 2050; therefore, satisfying people's water demands is a challenge [6]. In 1992, the International conference on water and the environment determined that the situation regarding water resources was becoming increasingly critical because researchers have demonstrated the planet is under stress because the water demand is 17% higher than what is available [1, 7]. These problems can cause a setback or even stop sustainable development, causing negative consequences for the ecosystems derived from water scarcity and unmeasured freshwater use [8]. Water scarcity raises three fundamental issues for the human population: maintaining food security (in the face of water constraints on agriculture), preventing a decrease in aquatic environment health, and averting political instability in international river basins [9].

Regarding availability, water is affected by agricultural, domestic, and industrial activities. Studies have determined these activities use around 50% of water directly to dilute contaminants, and other instream uses indirectly [10]. Since 1990, the domestic sector has raised its demand between 15% and 97%, depending on the country. In most countries, except for developed ones, water consumption has increased in the last decades due to economic and demographic growth, the evolution of living standards, and a larger supply of water systems. For example, irrigation represents around 70% of water withdrawals worldwide, and more than 90% of water consumption [1].

Currently, 10% of the population does not have access to drinking water, and the scenario for the future and even this decade is not positive [11]. Worldwide there are 2.6 billion people who lack basic sanitation facilities, more than 1.1 billion people have inadequate access to clean drinking water [12], and probably 1,800 million people will live in absolute water scarcity conditions. Additionally, two-thirds of the world population will be in stress conditions by 2025 [13]. Estimations say by the first quarter of the 22^{st} century, a quarter of the world population or a third of the population in developing countries will live in severe and extreme water scarcity conditions [5].

Water scarcity measurement characterizes through different metrics, the relationship between freshwater and human environments. The primary indicator is the *Water Stress Index* (WSI), which defines the stress level of a zone based on water availability. There is also an Inverted WSI, which measures the people supplied per flow units[1], and a Contemporary WSI threshold, which measures the volume available per capita per year. Table 1.1 shows the values of each version to characterize the scarcity level [14].

Table 1.1: Values of water stress index

	No stress	**Water scarcity**	**Water stress**	**Absolute water stress**
Contemporary WSI $m^3/capita-y$	>1.700	1.000 - 1.700	500 - 1.000	<500
Inverted WSI $p/flowunit$	<600	600 - 1.000	1.000 - 2.000	>2.000

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[1] 1 unit = $10^6\ m^3$.

Figure 1.1 shows projections for countries by 2040 in terms of the relation between the water supply available and how much water is extracted [15]. Compared to WSI, these values represent the ratio percentage of water withdrawal regarding total supply. The Chilean situation is critical because all the territory will have high or extremely high water-stress conditions.

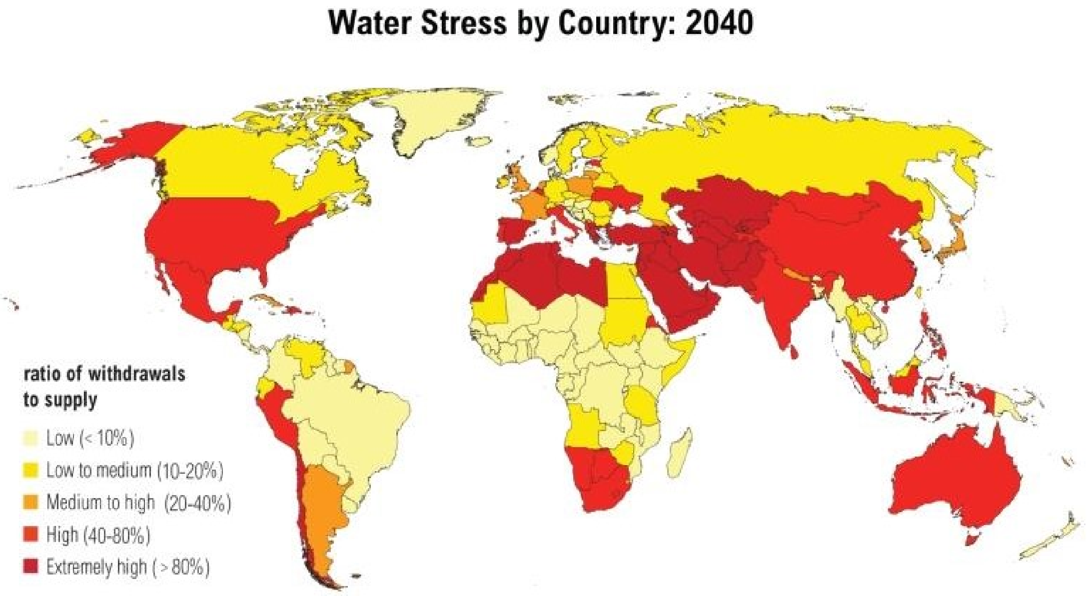


Figure 1.1: Aqueduct Projected Water Stress Country Rankings. Source: World Resources Institute (2015) [15].

1.2. Water allocation in the world

For water allocation, countries use different forms of governance for drinking water management. There are, principally, three models: Private Management (or market governance), State Management (or hierarchic governance), and Community Management (or network governance) [16]. For example, Ecuador's case depends on the city and the basin; and uses one or a combination of these management systems.

The *Private Management* model defines drinking water supply through the concession corporations who administer the resource. Nevertheless, these concessions do not possess a water property [16]. Countries such as Chile can be classified as this type of governance because 54 companies manage urban drinking water supply [17].

In the *State Management* model, the state must protect, preserve, and manage water sources to satisfy people's consumption needs through public entities [16]. For example, Belgium can be classified as this type of governance, where the *National Water Supply Society* is responsible for studying, establishing, and exploiting public water supply services [18]. In Israel, water is public; hence they are under the jurisdiction of the state, exclusively through the Water Commission (belonging to the Ministry of Agriculture). The water resources aim to satisfy the people's needs and the country's development. Besides, Israel has the following priority order for different water uses: 1. domestic, 2. agricultural, 3. industrial, 4. artisanal, commercial, and services [18].

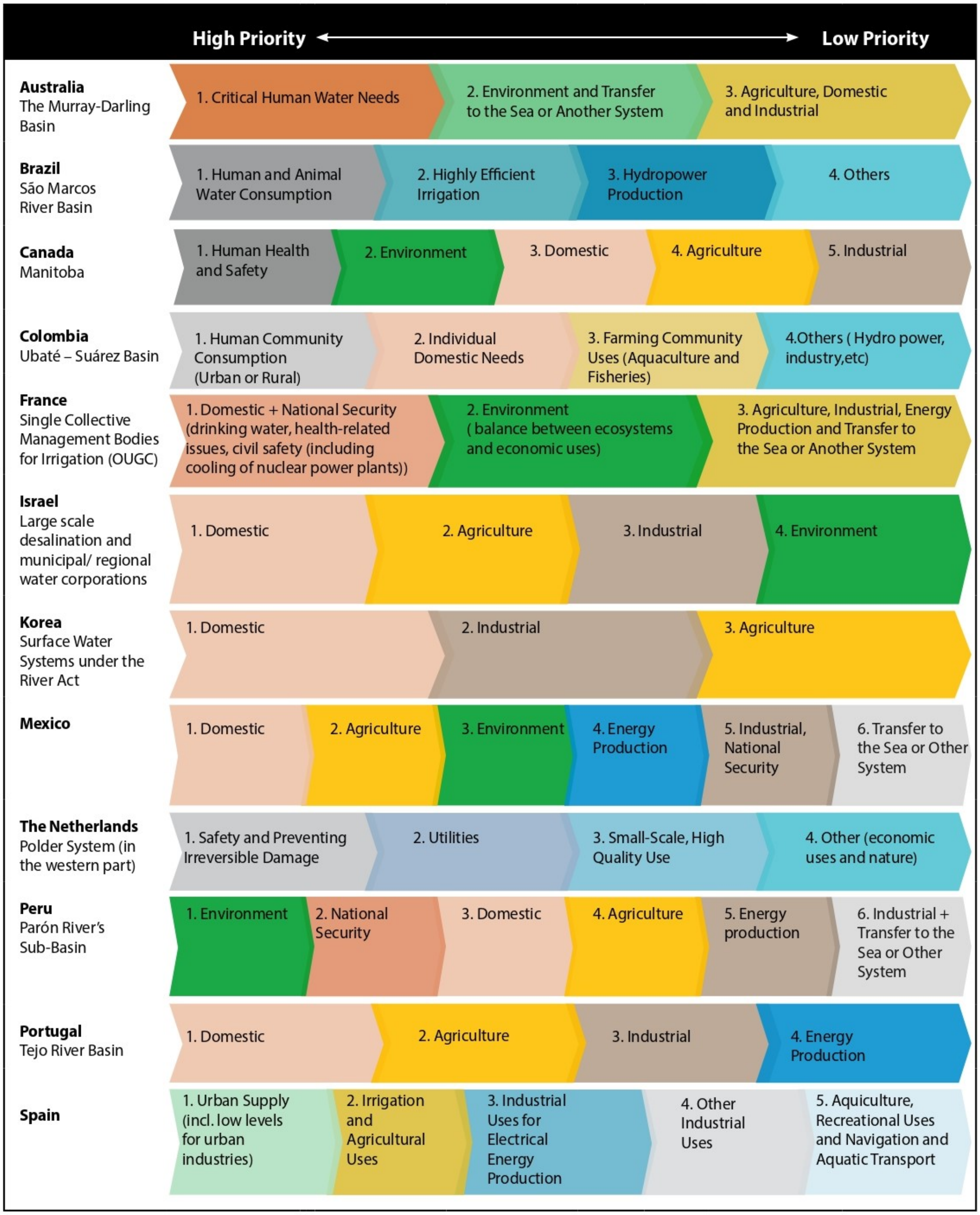
Finally, the *Community Management* model creates social structures formed by groups of people living in rural and peri-urban areas [16].

Regarding the legal framework, water allocation is addressed through *water rights*, which defines a property to access and use water bodies. These rights are administered and controlled according to the models described previously [19, 20]. They can be acquired because the water is on land, a person's property, or received by a legal arrangement. Worldwide, the current water rights grew out of past needs and were allocated during abundant water periods. Nevertheless, the current water scarcity scenario makes it necessary to change the understanding of water resources and their properties [20].

Additionally, in the legal framework context, Stephen Hodgson created the concept of *Water Tenure*, which is defined as *the relationship, whether legally or customarily defined, between people, as individuals or groups, concerning water resources* [21]. Water tenure differs from water rights mainly because it takes care of claims to specific water resources, understanding the relationship with the environment and its necessities, not just from a source. Tenure gives an integrated understanding of these relations and helps identify opportunities for better complex water uses. Besides, it regulates the abstraction of natural sources by defining the water uses, their purpose, time and usage intensity, and the conditions of their services (which ones and how) [21, 22]. Tenure arrangement also includes the *property right* concept, but it is more comprehensive and complex than a property right, which only involves rules and formal interactions between users [22].

Sustainable development of freshwater in the long term is essential. It must involve complete resource management and recognize the relation between elements compounding it and impacting its quality [8]. Research and guidelines have been developed to determine if water allocation is excellent or equitable. Some countries follow guidelines to make it more efficient. Water management must coordinate agricultural, urban planning, industrial, energy, and other policies to avoid conflicts of interest for the water resources [23, 24]. Three essential constraints for water resources management can be established: 1. water rights allocation must be compatible with the limited resource availability, 2. there must be sectorial coordination to prevent an excess of investment in infrastructure decreasing hydric ecosystems capacity, 3. instruments, such as economic incentives, price control, and taxes for water use, are needed to conserve the resource [23]. For example, in Colombia, the law establishes a *water use fee*, which means the water used for natural or legal persons, public or private, has a fixed payment for the national government. The payment destination is to protect expenses, and water resources renewal [25].

The answer to the question *how to allocate water?* depends on each country and its priorities. Figure 1.2 shows the different hierarchies of some countries. These hierarchies have been used to guide decision-making on water allocation systems [26].



High Priority ⟷ Low Priority

Australia The Murray-Darling Basin	1. Critical Human Water Needs	2. Environment and Transfer to the Sea or Another System	3. Agriculture, Domestic and Industrial			
Brazil São Marcos River Basin	1. Human and Animal Water Consumption	2. Highly Efficient Irrigation	3. Hydropower Production	4. Others		
Canada Manitoba	1. Human Health and Safety	2. Environment	3. Domestic	4. Agriculture	5. Industrial	
Colombia Ubaté – Suárez Basin	1. Human Community Consumption (Urban or Rural)	2. Individual Domestic Needs	3. Farming Community Uses (Aquaculture and Fisheries)	4.Others (Hydro power, industry,etc)		
France Single Collective Management Bodies for Irrigation (OUGC)	1. Domestic + National Security (drinking water, health-related issues, civil safety (including cooling of nuclear power plants))	2. Environment (balance between ecosystems and economic uses)	3. Agriculture, Industrial, Energy Production and Transfer to the Sea or Another System			
Israel Large scale desalination and municipal/ regional water corporations	1. Domestic	2. Agriculture	3. Industrial	4. Environment		
Korea Surface Water Systems under the River Act	1. Domestic	2. Industrial	3. Agriculture			
Mexico	1. Domestic	2. Agriculture	3. Environment	4. Energy Production	5. Industrial, National Security	6. Transfer to the Sea or Other System
The Netherlands Polder System (in the western part)	1. Safety and Preventing Irreversible Damage	2. Utilities	3. Small-Scale, High Quality Use	4. Other (economic uses and nature)		
Peru Parón River's Sub-Basin	1. Environment	2. National Security	3. Domestic	4. Agriculture	5. Energy production	6. Industrial + Transfer to the Sea or Other System
Portugal Tejo River Basin	1. Domestic	2. Agriculture	3. Industrial	4. Energy Production		
Spain	1. Urban Supply (incl. low levels for urban industries)	2. Irrigation and Agricultural Uses	3. Industrial Uses for Electrical Energy Production	4. Other Industrial Uses	5. Aquiculture, Recreational Uses and Navigation and Aquatic Transport	

Figure 1.2: Priority to allocate water by country. Source: OECD [26].

Besides, the countries have policies and regulatory entities to manage, protect, and allocate water resources. Different cases are described as follows:

- In Spain, there are River Basin Organisations. They have to elaborate, implement and assess each River Basin Management Plan (RBMP), administer and control the public water domain, grant licenses to water use rights, and regulate hydraulic works.

The RBMP sets a proportion limit for available water to abstract for consumptive uses. Regarding non-consumptive uses, the Hydrological Planning Regulation allows returning water to the environment without significantly altering its quality [27]. The entity in charge of allocating the water is River Basin Authorities. The allocation depends on demand, water availability, and social and environmental priorities. The system operating rules and the amount allowance estimation is made according to water planning documents [28]. The River Basin Plans determines the priorities of the use, which have the following hierarchy: 1. urban water supply; 2. irrigation and agricultural uses; 3. hydroelectric uses; 4. industrial uses; 5. aquaculture; 6. recreational uses; 7. navigation and water transport; and 8. other uses [28].

- In the case of Brazil, the ground and surface water is under public ownership. The federal domain includes rivers crossing or serving as state or national boundaries; the rest of the surface waters are under a state domain [29]. The state and federal water authorities control the allocation, applying the same criteria for the entire country; nevertheless, the River Basin Committee and Water Resources Authority regulate and allocate requests based on basin properties and needs. The priority to allocate water usage depends on the basin, but domestic and small-scale animal consumption usually are the primary uses. Besides, the River Basin Committee defines water use priorities scales, and water quality standards [30].
- In Australia, the Crown defines ground and surface water ownership. The Murray-Darling Basin Authority (MDBA) is the central entity for general water allocation regulation. It is in charge of the basin's policy and planning, ensuring integrated and sustainable management of resources through the Basin Plan. The MDBA calculates the amount allocated to each state from the Murray River. Then, water allocation depends on each state's management and water availability. For consumptive uses, the Basin States determine the allocation regimes for each river in the resource planning process. The Basin Plan must credit these plans because they specify resource management depending on the climate season. For example, in dry periods, water allocation decreases [31].

1.3. Natural resource accounting system

Based on all the water resources problems described, the need for more accurate accounting and tracking of its use arises. Generally, a natural resource accounting system involves national income and product accounting. Thus, these systems connect public policy analysis concerning non-market environmental goods or exhaustible natural resources and the economic activity of these resources [32]. According to Cabe & Johnson, *natural resource accounting combines concepts of national income and product accounting with the analysis of natural resource and environmental issues* [33]. Some uses of the accounting system information are the following [34]:

- It allows comparing the living standard through time.
- It allows comparing the living standard across countries.
- It can use as a sustainable consumption indicator.

The purpose of a natural resource accounting system is to collect information, such as the resource state or quality at a specific time, alterations reflecting pollution, or changes in environmental properties [34, 35]. These systems aim to create a systematic and coherent manner of quantifying the resource's state and registering them. Nevertheless, defining the resource state is very complex since it depends on its spatial disaggregation due to the high differences between the environmental quality in locations near each other; therefore, the system usually has a limited approach [35].

Natural resource accounting relates stocks and flows of environmental goods and services. The concept of balance is the most important in accounting. The analysis requires the stored amount at the beginning of the period, plus the input flows minus the output flows, to be equal to the stock at the end of the period. Hence, the following expression represents the balance equation [36]:

$$S_0 + I + N = C + E + M + S_1 \tag{1.1}$$

where S_0 is the stock at the beginning of the analysis period, I are the imports, N is the natural gain, C is the consumption, E are the exports, M is a natural loss, and S_1 is the stock at the end of the analysis period [36].

An example of a natural resource accounting system is the Norwegian hydropower accounting system. In 1978, the Central Bureau of Statistics of Norway created a system at the Ministry of Environment's request [35]. For resource selection, the Ministry established selection criteria defining why the accounting is needed: resource management has to improve and impact the governmental decisions, emphasizing sustainable development. Mainly, the resource must comply with the following aspects [35]:

- The resource to be analyzed must be economically or politically important.
- The resource must be important for human life quality.
- There has to be available data or statistics of the resource.
- The accounting has to be politically controversial due to economic interests in the resource.

The current climate change scenario makes it necessary to know the state of natural resources. Hence, these accounting systems are essential to control the more vulnerable resources and can take action when their availability decreases. For example, in Chile, the water resources have an availability problem, especially in the northern zone.

1.4. National Context

In the case of the national scenario, Chile's geographic location grants privileged water resources availability; nevertheless, Chile is among the top thirty countries under water risk [37]. Water demand has increased for industrial and agricultural uses, and reserves as Andean glaciers are decreasing due to climate change, reducing water availability [1, 37, 38]. Besides, Chile presents water heterogeneity, which means there is an imbalance between zones with more water supply and zones with more water demand, the south and the north of the country, respectively [37]. According to the WSI, seven of the fifteen regions are at least in water stress (see Figure 1.3 [39]). In fact, an agricultural emergency due to water deficit[2] was declared in 194 communes (56%) due to drought in 2015 [37].

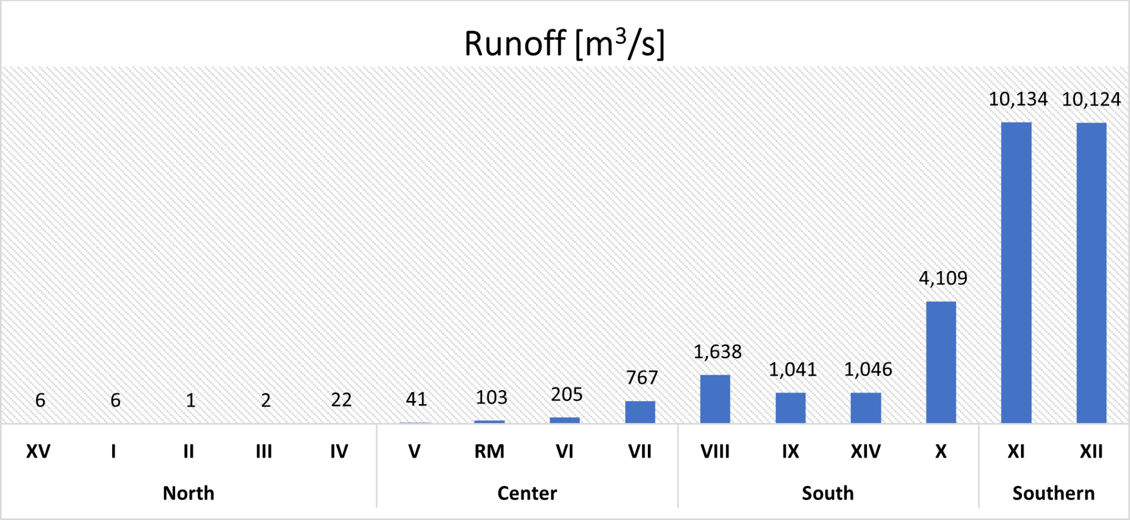


Figure 1.3: Total available flow: runoff by region and macrozone.

The country's northern zone is imbalanced between water supply and demand due to the domestic and mining industry's water needs. The mining industry has a high water demand, overexploiting surface water, and groundwater sources [38]. Regarding the supply, storms occurring in the high Andes Cordillera feeding small streams and recharging the aquifer system is the only source of supply [41]. The Atacama Desert, which concentrates most of the country's mining activity, also registers the lowest level of precipitation worldwide [41, 42].

In Chile's central zone, there is a deficit in snow and rain and an increase in temperatures [43], which have decreased the river's main mean flow and native vegetation. Annual precipitations have decreased for the southern and north of the austral macrozone, and projections are unfavorable if the average temperature still increases. In the worst case, models expect a reduction of 4% and 8% in precipitation for those zones, respectively [44]. Figure 1.4 shows drought effects between 2010 and 2015 in rainfall, streamflow, and the maximum and minimum temperatures in most Chilean territories.

Based on water resources problems, countries need proper water management. Chile created the Water Code in 1981, which specifies water rights as the water allocation system allocates water to users. Once the users have water property, they can commercialize their rights through the water market or reallocate them. The water market's theoretical function is to regulate the reallocation of available water resources based on economic efficiency [45]. Nevertheless, because of the allocation of rights and the Water Code, there are over-awarded basins in which the distributed flow exceeds the basin's capacity [46]. Besides, most water rights are not declared, and the information is unclear. For example, studies revealed that water use rights, both consumptive and permanent, registered in the General Water Department database, are around six times greater than water collection at the national

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[2] Tool of the Ministry of Agriculture to provide help and support for the country's areas affected by water lack [40].

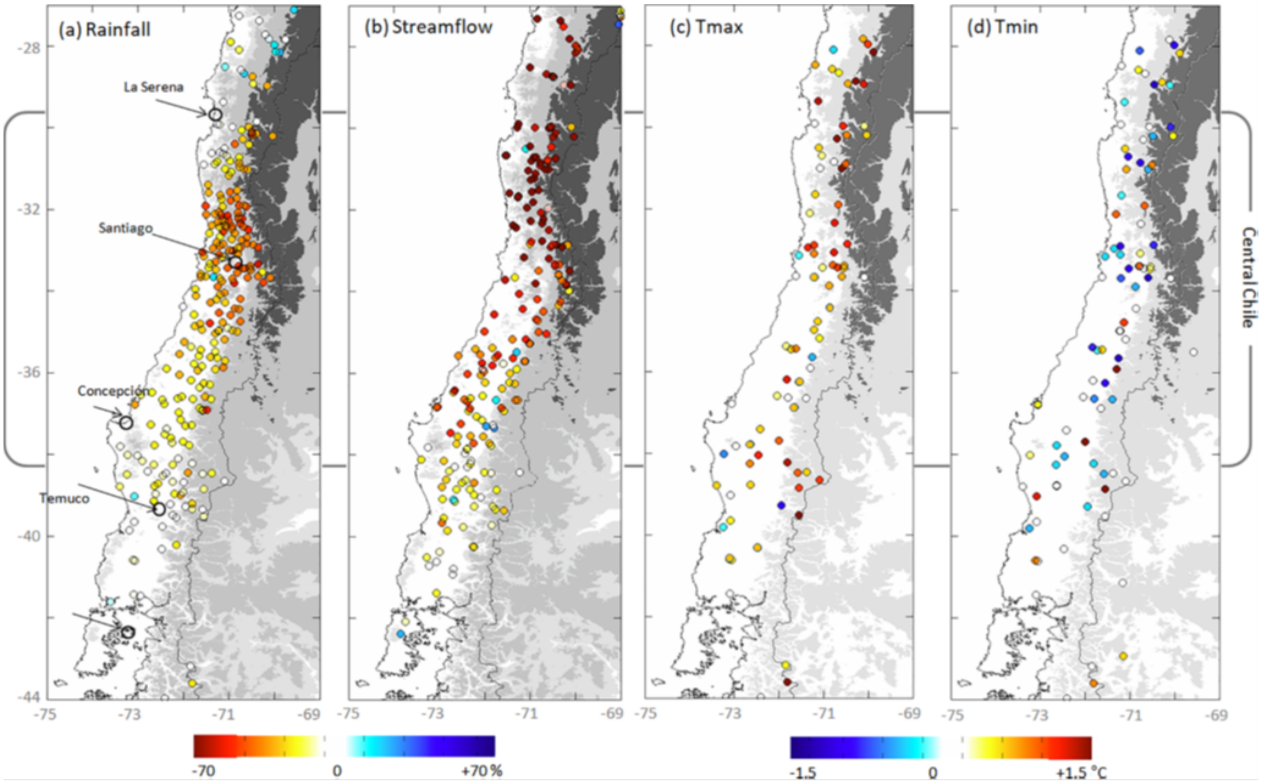

Figure 1.4: Station-based anomalies during the drought: (a) rainfall, (b) river flow, (c) maximum temperature, and (d) minimum temperature. Source: Garreaud et al. (2017) [43].

level [37, 47]. These situations reflect inefficient water management and the necessity of a consolidated national policy to preserve resources and protect the human right to water.

The General Water Department (DGA for the acronym in Spanish) is a state body aiming to regulate and manage water resources by managing, verifying, and disseminating water information in the country [48]. Its principal function is *planning water resources development in natural sources to formulate recommendations for its exploitation* [49], and its main guideline for the 2018-2022 period is the *strategic management for basins* [50]. Although DGA has information and resources to improve the system, they do not play an explicit role in the security of the drinking water supply.

Another DGA function is to decree *water scarcity* when a zone suffers extraordinary drought. This classification depends on hydrometeorological criteria: precipitation data, river flows, reservoir volume, and aquifer conditions. From 2008 to April 2021, the DGA issued 167 water scarcity decrees. Figure 1.5 shows how decrees have increased over recent years [51].

These difficulties produce a problematic relationship between water resources and their management in Chile, making it challenging to consolidate a national policy. The institutional framework is complex, mainly due to the high number of actors involved and other obstacles increasing the problem, such as the following [47]:

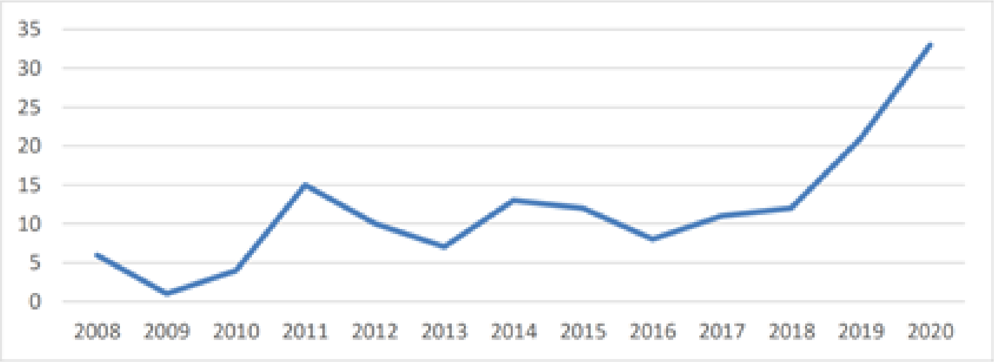

Figure 1.5: Number of water scarcity decrees in Chile 2008-2020. Source: Pablo Morales (2021) [51].

- Lack of transparency in the water market at the basin level.
- Disagreement of institutions at the basin level due to water resources management by sections.
- Limited, partial, and contradictory information about water resources, causing distrust between actors.
- Low control of users.
- An inadequate institutional and regulatory framework for integrated water resources management in a basin.
- Lack of knowledge and authority about illegal water extractions.

Besides all these problems, one of the nation's main problems is not recognizing water access as a human right. Inefficient management of water resources and ineffective decision-making make it necessary to strengthen the governance system [42]. The above problems show that reaching a concept involving water rights and access as human rights is essential in Chile.

Therefore, the need to solve the water resources allocation problem and have broader water resources protection concepts arises. Solving the allocation problem must consider more than one parameter; for example, different indicators can assess the water resources, aiming to improve water management. Hence, to study this problem, the analysis has to be carried out from different perspectives, such as considering supply and demand, quality, economy, and human health. Nevertheless, currently, no indicators assess the allocation; there are only metrics to determine the scarcity. Therefore, the present work proposes the creation of a vectorial assessment indicator for water allocation evaluating the quality of water resources allocation in a basin determined by a zone's availability and necessity. The motivation for creating a vectorial indicator is the importance of considering different aspects to assess water use and have a better approach to how water is utilized. In this case, these assessments are the use of water in consumptive uses relative to their demand, the use of water in non-consumptive uses relative to their demand, and pollution caused for mixed uses. The decision to have three values separately is not to lose information about the status of each one. A case study applies the vectorial assessment vector through solving an optimization problem, which decides the water allocation in a specific basin, using the vectorial measure as a supporting tool. The goal is to find an efficient distribution in the selected location regarding allocated water for each use, considering the environmental consequences of the allocation. The efficiency measure will mainly depend on the demand fulfillment of the water uses [52].

The indicator creation will be based on a water accounting system. This accounting system aims to quantify three aspects: i) availability in each basin of a country; ii) the extracted water flow by specific use in thousands of cubic meters per year (km^3/y); and iii) social, economic, and environmental consequences of these uses. The election of these aspects is because the system will be used as a tool to create the indicator, then it has to be related to the assessments purposed of the indicator.

1.5. Research Questions

1. In a hydrological basin, what distinguishes an efficient and equitable resource allocation from a deficient one?
2. What mathematical expression could quantify an equitable resource allocation?
3. Considering the previous question, how can we suggest a hierarchy of changes in basin management to improve its water allocation?

1.6. Objectives

1. Identify aspects of efficient water allocation for the different uses: main domestic, agricultural, industrial, and ecosystem maintenance.
2. Create an accounting system encompassing multifactorial aspects and the use and objective of the water allocation for a determined use.
3. Build mathematical equations to define a vectorial assessment indicator for water allocation depending on a zone's economic, environmental, and social aspects.
4. Analyze the performance of the vectorial indicator from a water tenure perspective to incorporate this new concept and a different legal framework outlook. This analysis aims to incorporate a broader understanding of the relationship between water and society.
5. Illustrate the potential vectorial indicator use through a case study in a basin in Southern Chile, formulating an optimization problem to propose an efficient scenario to improve its water allocation.

1.7. Thesis organization

This work is composed of six chapters and an Appendix section. Chapter 1 briefly introduces this work; it presents information about the problem, its motivation, and its contributions. In addition, it presents the objectives and research questions. Chapter 2 defines and discusses the water accounting system necessary to create a new indicator.

Chapter 3 covers the indicator creation and the base for this definition and discusses it. Chapter 4 presents the water tenure concept, background, definition, and uses. Chapter 5 tries the indicator in a case study through an optimization problem and discusses its results. Finally, chapter 6 presents the concluding remarks and indicator projections.

Chapter 2

Defining a water accounting system

This chapter defines a water accounting system needed to create an indicator, defining an accounting system specific to water resources based on the Chilean scenario and necessities. The accounting system is based on the Chilean case.

2.1. Application of the natural resource accounting system to a national problem

As presented in the introduction, water resource availability and allocation is an increasingly urgent problem in Chile and the world. In addition to water scarcity in the country, the allocation and management problem decreases people's quality of life, particularly in the north and north-center zones [53]. In this context, the present Section defines a Water Accounting System (WAS) needed to create an indicator. The WAS objective is to quantify three aspects, which are explained and justified in the following:

1. Availability in each basin of a country.
   There is high variability in the supply across the country; therefore, knowing the principal water source to provide a determined zone is necessary. Given the significant variation in scarcity levels between the country's north, center, and south, each basin needs a plan to preserve the water resources and supply the different uses of water based on basin availability [53].

2. The extracted water flow by specific use, in thousands of cubic meters per year (km^3/y).
   Different uses need a different priority. Figure 1.2 shows that different countries have a priority hierarchy for water allocation. In a scarcity scenario, the allocation could not be enough to supply the demand of all uses. Hence, knowing the use of the resource is necessary for decision-making.

3. Social, economic, and environmental consequences of these uses.
   The selection of who uses the water has economic, socio-cultural, environmental, and health consequences. For example, agriculture significantly contaminates water, decreasing its availability, which has economic consequences. It can affect water chemistry due to eutrophication and food modification, biocide leaching and pesticide use, and alter hydrological cycles [54, 55]. Indigenous people are the most affected at a socio-cultural level because water is a cultural heritage defining their identity and traditions. Entire communities have to migrate by the lack or pollution of water,

in particular in the northern zone, because of mining activity [55–57]. Finally, at the environmental level, the natural resource exploitation projects (e.g., mining and aquaculture) negatively affect ecosystems and imply supply problems of natural services, such as water [55]. For example, in the II region increased water scarcity when the Water Code was applied in 1984 because water rights were granted to mining big companies. Nevertheless, these rights had belonged to indigenous communities for hundreds of years but were not formally registered [57].

Although accounting relates the environmental and economic resource perspectives, this system aims to describe the relationship between the resource and the environment without considering the financial perspective. This work mainly focuses on the environmental behavior study of water to analyze the water use priorities for society and ecosystems, not allowing economic interests to affect the decision-making.

The WAS will be connected with Water Footprint (WF) because it is a helpful tool to measure aspects of water use and its consequences. The WF measures the water volume used to produce all the goods and services to supply the needs of humanity [58]. It is an indicator to calculate spatial and temporal freshwater consumption and measures each stage of the production process and value chain [58]. There are three components of WF: green WF, blue WF, and grey WF. The green WF refers to the total rainfall which temporarily stays in soil moisture or vegetation. This water will evaporate from the ground surface and is evapotranspired from vegetation or incorporated into it[58]. Then, the blue WF indicates the fresh surface volume or groundwater consumed in producing goods and services. It is the water evaporated volume, incorporated into the product, or returned to a different location in another period, regarding its withdrawal [58]. Finally, the grey WF is a pollution measure expressed as the volume of water required to assimilate the pollutant load to meet environmental water quality standards [58]. Figure 2.1 shows WF elements and where each one is measured.

The water accounting system definition needs two steps. First, identifying main water uses in Chile; then, determining parameters to account for each use. The different uses and destinies are domestic, agricultural, mining, livestock production, environmental protection[3], forest industry, hydropower, and aquaculture [59]. These uses follow the classification of consumptive and non-consumptive. In consumptive uses, there is a difference between supplied volume and discharge volume because the productive activity consumes the water in the process. In the case of non-consumptive uses, they do not consume water in the process, and the discharge volume is equal to that of the supplied volume [60]. In this work, consumptive uses (C) are domestic, agricultural, mining, livestock production, and environmental protection and will be denoted by the subscript i [59, 61]. The non-consumptive uses (NC) are forest industry, aquaculture, and hydropower and will be denoted by the subscript j [59, 61]. Finally, mixed uses (B) will utilize the subscript i or j for consumptive and non-consumptive uses, respectively.

The water accounting system is composed of three categories: 1. consumptive uses (WAS^C), 2. non-consumptive uses (WAS^{NC}), and 3. mixed uses (WAS^B). The first category goal is to determine whether, for a specific activity, the water supplied is sufficient

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[3] The environmental protection use is related to environmental flow

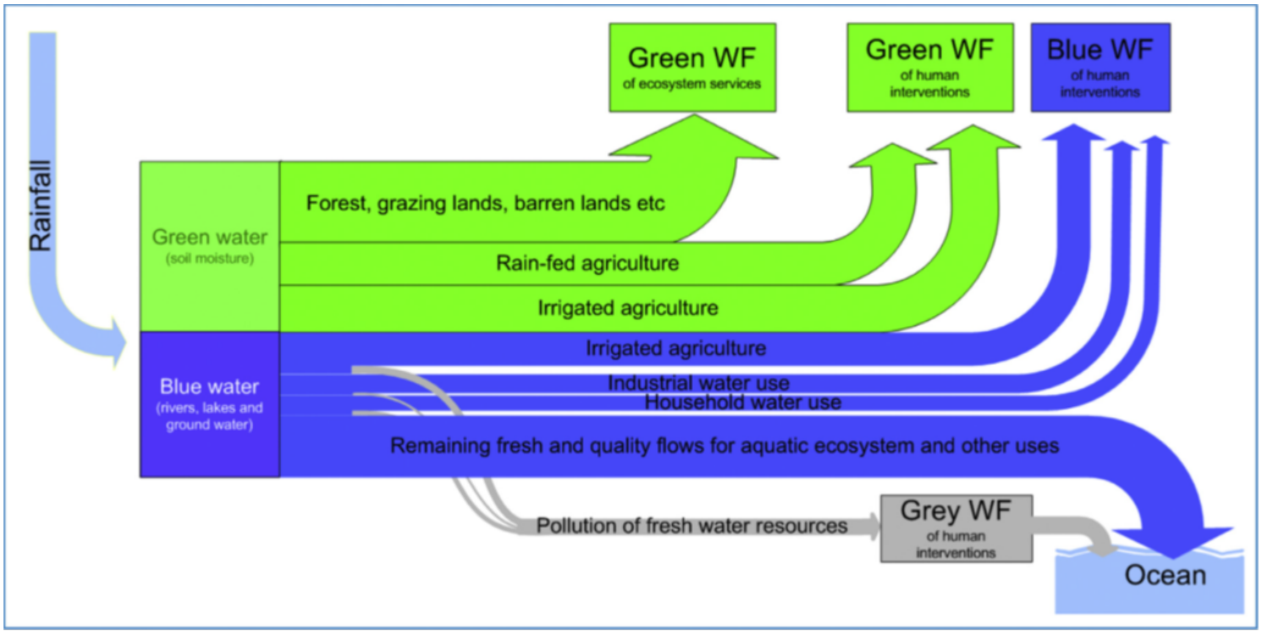


Figure 2.1: Relationship between water resources and green, blue, and grey WF. Source: Chapagain (2017) [58].

for its requirements through the relation between demand and water withdrawals. Then, the second category goal is to quantify the water commitments and requirements for each use. Lastly, the third category goal is to determine the proportion between water used and water polluted through grey WF.

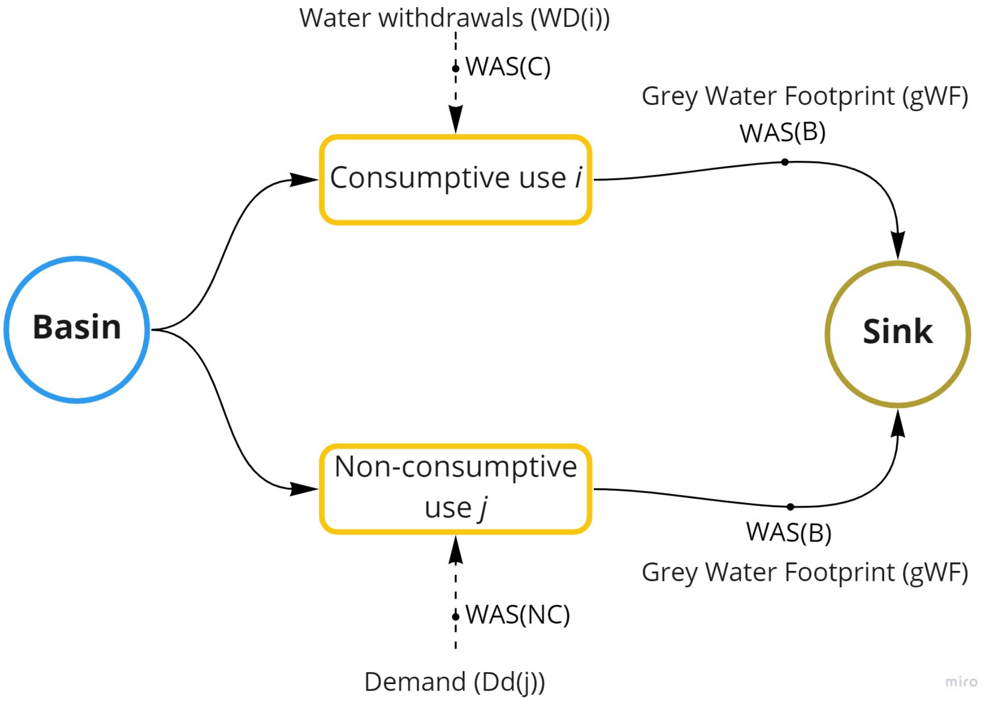


Figure 2.2: Simplified representation of the Water Accounting System.

Figure 2.2 shows a short diagram representing the system. A basin has to supply two uses, consumptive (i) and non-consumptive (j). The consumptive use i utilizes an amount of water WD_i to satisfy its requirements, which comes from the basin. The non-consumptive use j utilizes an amount of water Dd_j to satisfy its demand, which also comes from the basin. If their uses cause water pollution, they will have a grey water footprint associated; for use i will be gWF_i, and for use j will be gWF_j. Then the WAS for this basin will be determined for consumptive uses by $WAS^C = WD_i$, for non-consumptive uses by $WAS^{NC} = Dd_j$, and for pollution by $WAS^B = gWF_i + gWF_j$. The water is not returned to the basin. Then the system considers a sink for the water used by the processes; it can be treated or proceed to another water body.

Generally, the Water Accounting System is defined for each water use as follows:

1. For one consumptive use,
$$WAS_i^C = WD_i,\ i \in C \tag{2.1}$$
where WD_i is the water withdrawals of use i.
2. For one non-consumptive use,
$$WAS_j^{NC} = Dd_j,\ j \in NC \tag{2.2}$$
where Dd_j is the non-consumptive demand of use j.
3. For any of both uses,
$$WAS_k^B = gWF_k,\ k \in B \tag{2.3}$$
where gWF_k is the grey WF of the use k.

Table 2.1: Water Accounting System table representation.

	WAS^C	WAS^{NC}	WAS^B
Consumptive uses			
Use i	WAS_i^C	-	WAS_i^B
Use $i+1$	WAS_{i+1}^C	-	WAS_{i+1}^B
Non-consumptive uses			
Use j	-	WAS_j^{NC}	WAS_j^B
Use $j+1$	-	WAS_{j+1}^{NC}	WAS_{j+1}^B

2.2. Discussions

This chapter presents a water accounting system to measure the water consumption and pollution of the different uses in a basin. Based on the Chilean case, the uses are classified as consumptive and non-consumptive to account for water consumption. In water pollution, the accounting is for both.

The water accounting system, defined by Equations 2.1, 2.2, and 2.3, is constructed based on demands and grey water footprint, as is shown in Table 2.1. The goal of WAS creation is to have an instrument for summarizing the basin situation regarding demand fulfillment and water pollution, facilitating the improvement proposal to change the basin state. Hence, the system becomes necessary for indicator creation. It allows comparing the current basin situation with an ideal fictional scenario, defining the WAS for both.

The system aims to be applicable in any country because the focus is on the consumptive uses, the non-consumptive uses, and pollution for both. Then the three components need to be defined and separately characterized. Thus, the uses to be considered can change depending on the region to be studied without affecting the WAS objective because the purpose is to know the basin state regarding the water consumed.

The WAS is constructed based on the available information. Nevertheless, it could be more accurate by including specific data about withdrawals and return flows for each use. It could add the assessment of specific quality parameters for more complex accounting. For example, it calculates the impact in the sink, knowing the quality parameters and the destiny of the return flow. These aspects were not considered in this work because they are away from the study scopes; nevertheless, they could be used to better the analysis in future research.

Lastly, the system can be a tool to warn when the basin is being over-exploited, considering the variation in the basin volume based on the extracted water. The WAS has data about withdrawal flows, and by adding climate factors, such as precipitations, in a mass balance, the basin information can be more accurately represented.

Chapter 3

Assessing the water allocation in a basin: a vectorial indicator

This Chapter creates the vectorial indicator. The first Section defines the ideal scenario for each use regarding water use and pollution caused. Then, the second Section defines the indicator equations.

The definition of a vectorial water allocation indicator (VWAI) depends on two water accounting systems: the first indicates an ideal context, and the second indicates the current context (determined by WAS) regarding the allocation. The vectorial indicator is a comparison measure of these systems, which aims to show the basin state concerning the water requirements and contamination. The indicator is a comparison through a deviation measure. This structure allows the assessment and dimension of how close or far the allocation is from a desired objective, which would facilitate the decision-making for the entities. Besides, it is easy to calculate and interpret, showing if the resource is over-supplying or under-supplying by the different uses and how much they pollute.

3.1. Defining the ideal scenario

The indicator is a tool for comparing the current and ideal situation regarding the allocation. Hence, this Section defines the ideal scenario regarding how much water the uses need and how much they can pollute the water.

The Ideal Scenario (ID) formulation for each use is assessed through bibliographic information based on the research. The nomenclature ID^C represents the ideal demand for consumptive uses, ID^{NC} represents the ideal water requirements for non-consumptive uses, and ID^B represents the ideal pollution for mixed-use. The uses classification in consumptive and non-consumptive follows the detailed description of Section 2.1.

3.1.1. Ideal scenario for consumptive uses (IS^C)

This Section defines how to calculate the ideal flow of water demand for consumptive uses (see Figure 3.1) based on the characteristics and requirements of each use.

In the case of agriculture, mining, and livestock production uses, the water demand depends on different species. For this work, 85% of the main species are considered to simplify the calculus, maintaining a good approach to the real value.

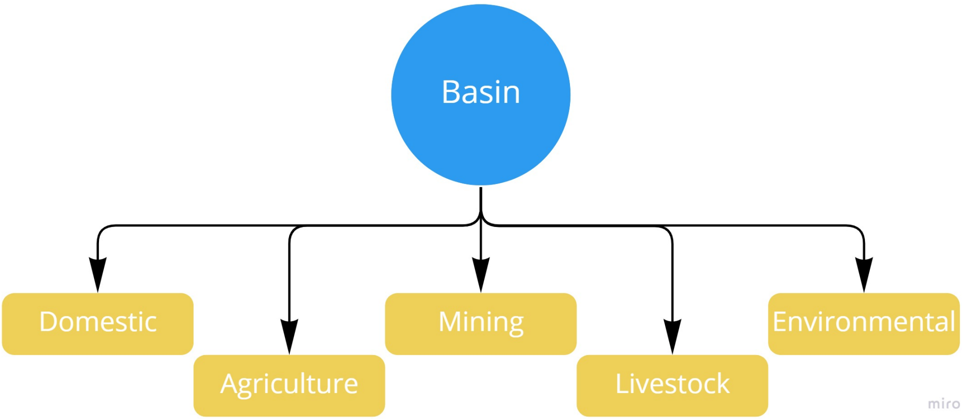


Figure 3.1: Consumptive uses.

3.1.1.1. Domestic

In 2003, the United Nations Committee on Economic, Social and Cultural Rights determined for humans the right to *sufficient, safe, acceptable, physically accessible, and affordable water for personal and domestic uses* [62]. This use defines the minimum water flow required for people's basic needs such as drink, food preparation, basic hygiene, healthy urban life, and bath and sanitation to ensure sustainability [63]. The domestic flow estimation depends on the people supplied by the basin and the flow used per person. Equation 3.1 shows the ideal scenario definition for domestic use (IS^{C}_{dom}).

Figure 3.2 shows a graphical representation of domestic water use, in which a basin supplies a community of P persons, each with an annual water consumption of Qp. This value takes a realistic approach to the urban lifestyle level [63].

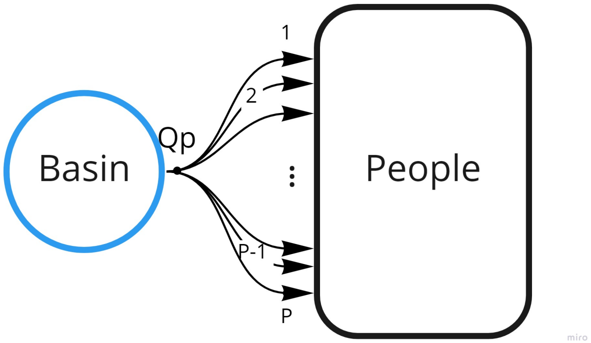


Figure 3.2: Graphical representation of flows involved in domestic use.

The following equation represents the ideal scenario definition for domestic use

$$IS^{C}_{dom} = P \cdot Qp \tag{3.1}$$

in which P is the population supplied by the water in a specific basin, and Qp is the water consumption for one person per year.

3.1.1.2. Agriculture

Determining water requirements for a crop depends on the water loss through evapotranspiration. Precipitations, irrigation, or both can supply this need. When the rainfalls are not enough, irrigation is needed. The quantity of water calculated in this section corresponds exclusively to water coming from a natural source [64]. The methodology used is the same as described in the *Irrigation Water Management: Training manual nº3* of the Food and Agriculture Organization of the United Nations (FAO) [64].

The water requirements depend on the climate and the crop type. Thus, the crop factors (Kc_{crop}) and reference crop evapotranspiration (ET_0) determine the water demand for a specific crop (ET_{crop}). The reference evapotranspiration is determined by the climate conditions of the zone, as shown in Equation 3.2 [64].

$$ET_{crop} = Kc_{crop} \cdot ET_0 \tag{3.2}$$

The root zone only partially uses the rainwater; then, just a part of the rainfall supplies their requirements. Equation 3.3 represents the water effectively used from precipitation (Pe) for the crops depending on monthly rainfall (Pm) of the zone [64]. This work does not consider the water not used for the crops because it does not affect the study system.

$$Pe = \begin{cases} 0.8Pm - 25 & \text{if } Pm \geq 75\frac{mm}{month} \\ 0.6Pm - 10 & \text{if } Pm < 75\frac{mm}{month} \end{cases} \tag{3.3}$$

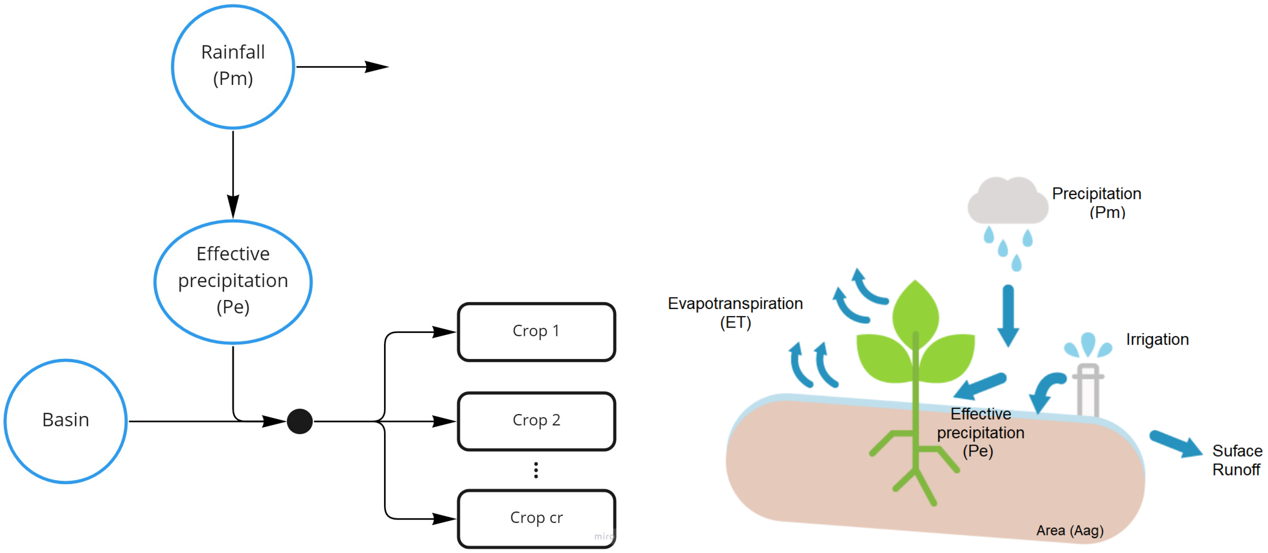
Figure 3.3 shows two graphical representations of agricultural water use in which a basin supplies the water requirements of different crops when the water of the rainfall (Pe) is not enough. Then, the requirement of each crop cr depends on its total cultivation area Aag_{cr}, its crop factor Kc_{cr}, and the zone's evapotranspiration ET_0. For more information, see Appendix A.

Finally, the irrigation water need depends on the crop water need, the precipitations, and the area to irrigate [64], as is shown in Equation 3.4.

$$IS^{C}_{ag} = \frac{\left(\sum\limits_{cr \in Cr} ET_{cr} - Pe\right) Aag_{cr}}{\eta} \tag{3.4}$$

in which Cr is the set of principal crops in the zone, $A_{ag,cr}$ is the crop area to irrigate crop cr, and η is the irrigation system efficiency. The crop coefficient value depends on the growth stage as shown in Figure 3.4 [65]. Then, to determine Kc_{crop}, the values at the beginning, at the middle, and the end of the crop were adjusted by a weighted sum (see Appendix A).

For the Cr set, the main species in the zone were taken, corresponding to 85% of the crops produced.



(a) (b)

Figure 3.3: Graphical representation of flows involved in agriculture use.

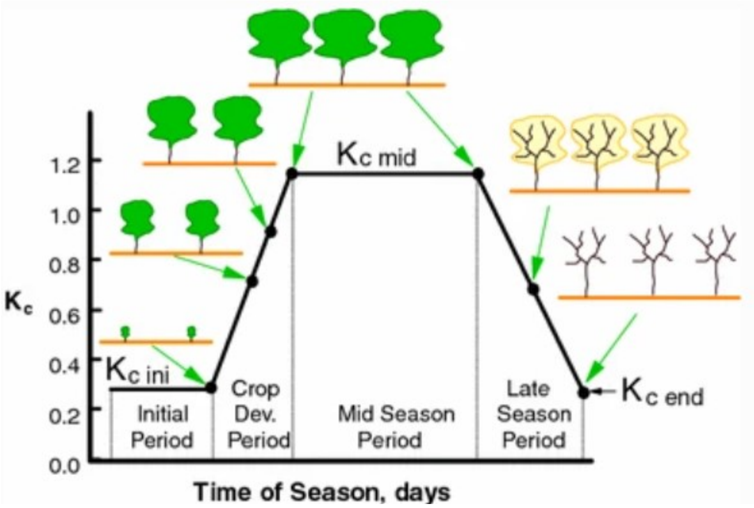


Figure 3.4: Crop growth stage. Source: Allen and Pereira (2009).

3.1.1.3. Mining

In mining, water has different uses depending on which operational activity is supplied, such as [66]:

- Transport of minerals and waste in slurries and suspension.
- Separation of minerals through chemical processes.
- Physical separation of material, such as in centrifugal separation.

- Cooling systems around power generation.
- Suppression of dust during mineral processing and around conveyors and roads.
- Equipment washing.
- Dewatering of mines.

When utilizing a coefficient, it must include the water demand for all these needs. This factor represents how much water is required by all the mining processes regarding the mass of each treated mineral, as shown in Equation 3.5.

Figure 3.3 shows a graphical representation of mining water use, in which a basin supplies the water requirements of different minerals. The mass to be treated of the mineral m is MM_m and has a water consumption rate of f_m.

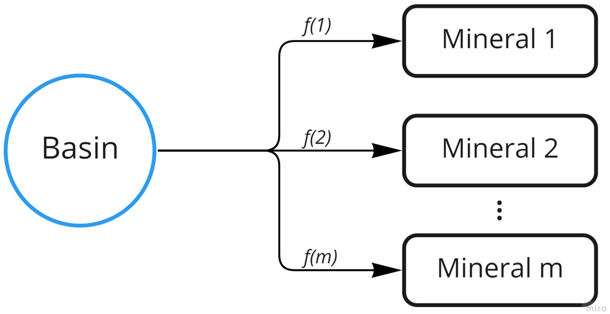


Figure 3.5: Graphical representation of flows involved in mining use.

$$IS^C_{min} = \sum_{m \in M} f_m \cdot MM_m \tag{3.5}$$

in which f_m is the consumption rate for mineral m, MM_m is its mass to process per month, and M is the set of main minerals produced by the country, which compose 85% of national production.

3.1.1.4. Livestock production

In livestock production, several types of animals consume water, and each animal has a different water requirement depending on its size and growth stage [67]. This thesis utilizes a simplified version for calculating water needs; hence it takes 85% of the principal species (A) produced in the country. Besides, it will consider water consumption corresponding to adult animals.

Figure 3.6 shows a graphical representation of water use for livestock production, in which a basin supplies animals' water needs. Species a has a total of na_a animals, and each has a water requirement a_a. Equation 3.6 shows the calculation for the total water requirement of this use.

$$IS^C_{lp} = \sum_{a \in A} a_a \cdot na_a \tag{3.6}$$

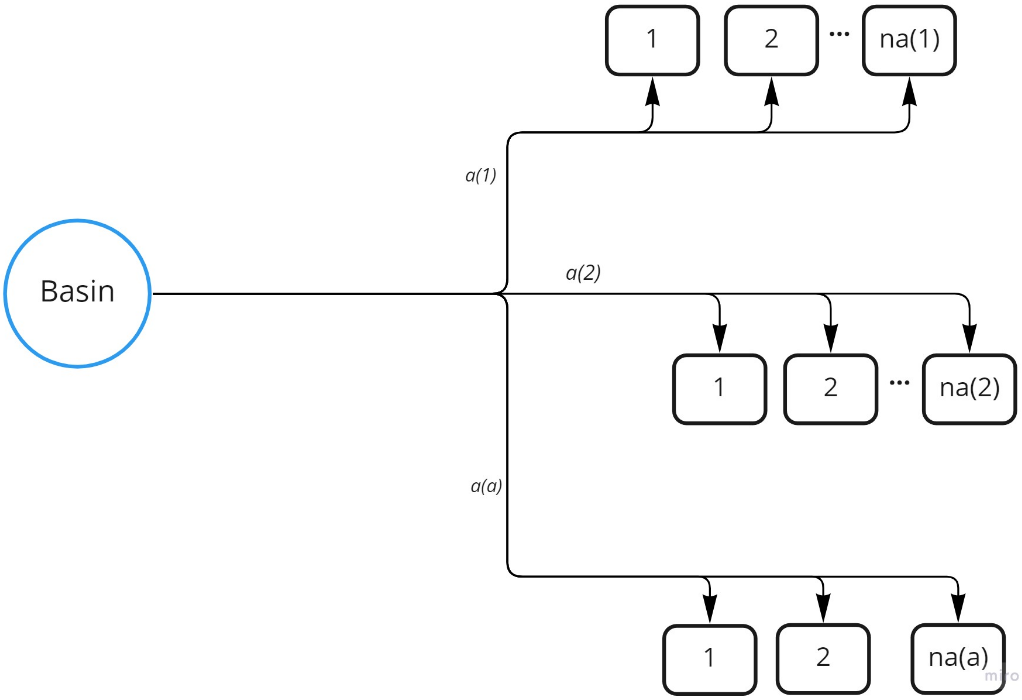


Figure 3.6: Graphical representation of flows involved in livestock production use.

in which a_a is water consumption per animal per year for species $a \in A$, and na_a is animals number for species $a \in A$ in the zone supplied by the water basin.

3.1.1.5. Environmental protection

Environmental flow is defined as the *quantity, timing, and quality of water flow required to sustain freshwater and estuarine ecosystems, and the human livelihoods and well-being depending on these ecosystems* [68]. In other words, there has to be a reserved flow for an ecosystem's security and for the complete development of the region.

In case there are no studies of the basin and its requirements to characterize its needs, the evapotranspiration produced by the basin vegetation was considered a reference to estimate this flow, aiming to ensure the water requirements for the basin vegetation.

$$IS_{ep}^{C} = ET_{basin} A_{basin} \tag{3.7}$$

in which ET_{basin} is the evapotranspiration basin requirements and A_{basin} is the basin area.

3.1.2. Non-consumptive uses (IS^{NC})

This Section defines how to calculate the ideal flow of water requirements for non-consumptive uses (see Figure 3.7) based on the characteristics and needs of each use.

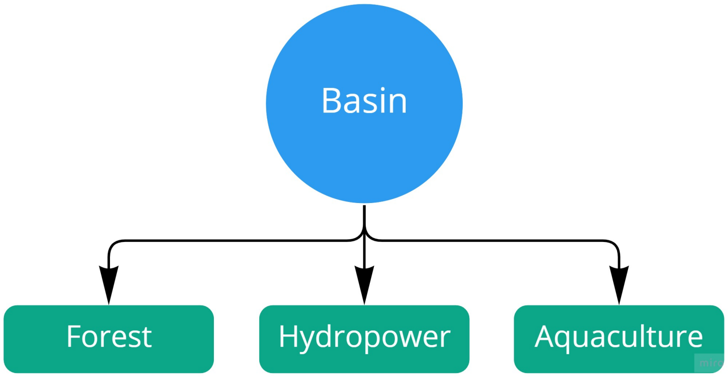


Figure 3.7: Non-consumptive uses.

3.1.2.1. Forest industry

This model supposes water used in forests is provided only from rainfall; hence it is considered a non-consumptive use type. For this use, it assumes all water from precipitation is available to supply the forest's water needs without additional irrigation. Figure 3.3 shows a graphical representation of forest industry water use, in which a forest of area $Afor$ receives an annual amount of water Pa from precipitations. Equation 3.8 describes the calculus for the ideal scenario of the forest industry.

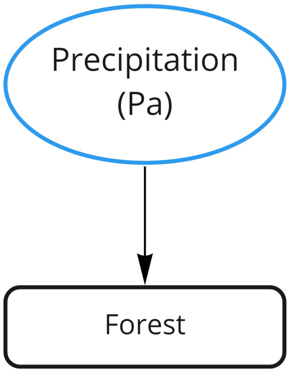


Figure 3.8: Graphical representation of flows involved in the forest industry use.

$$IS_{for}^{NC} = Pa \cdot Afor \tag{3.8}$$

in which Pa is the annual precipitation per unit surface area, and $Afor$ is the area used for forest plantations.

3.1.2.2. Hydropower

Water used in hydropower is part of a cycle of energy generation through turbines; hence, the water is used and returned to the river [69]. For this reason, the analysis assumes the returned flow equals the withdrawn flow. Figure 3.3 shows a graphical representation of hydropower water use, in which a basin gives a flow Qw to hydropower plants, and they have to return a flow Qr equal to Qw.

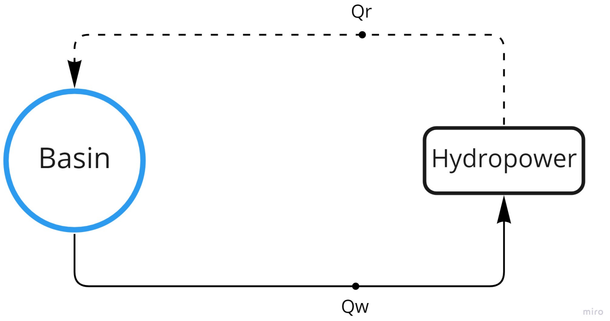


Figure 3.9: Graphical representation of flows involved in hydropower use.

In the ideal scenario, the returned flow (Qr) is equal to the withdrawal flow (Qw), as is shown in Equation 3.9.

$$IS_{hp}^{NC} = Qw \tag{3.9}$$

3.1.2.3. Aquaculture

Chilean aquaculture uses the system flow-through, where there is a withdrawal and returns flow to the source. The requirements are calculated based on the flow to correctly maintain the species raising and dissolved oxygen and carbon dioxide concentrations. This analysis takes the principal species (F) produced in the country, corresponding to 85% of national production.

Figure 3.3 shows a graphical representation of aquaculture water use, in which a basin supplies species' water needs. Equation 3.10 shows the calculus for the entire water requirement of this use. The species f have a total production of M_f mass and needs a constant water flow q_f for its raising.

$$IS_{aq}^{NC} = \sum_{f \in F} q_f \cdot M_F \tag{3.10}$$

in which q_f is the water flow requirement for species $f \in F$ and $M_f \in F$ is the system's total mass of species f.

3.1.3. Pollution for both uses (IS^B)

Currently, there are different water treatments, depending on their provenance or the objective of water treatment [70]. For this reason, the purpose of each use, for the ideal case, is to produce the least quantity of water pollution, aiming to promote an improvement in

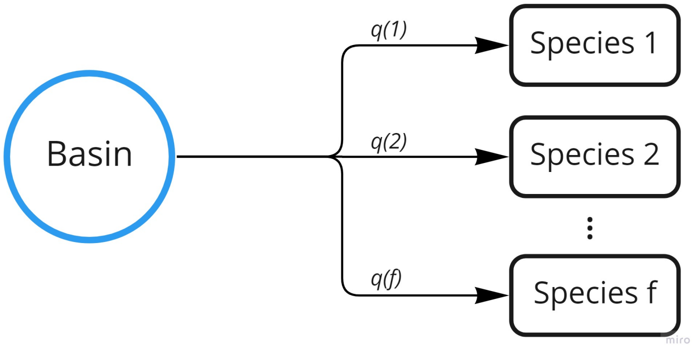


Figure 3.10: Graphical representation of flows involved in aquaculture use.

water quality, protection, and conservation.

$$IS_k^B = 0\,\forall k \in B \tag{3.11}$$

in which k represents each case of mixed uses (B)

3.2. Defining a vectorial water allocation indicator

This section creates the vectorial water allocation indicator based on the ideal scenario and the accounting system definition. Given that both methodologies have three components (consumptive, non-consumptive, and pollution of mixed uses), the indicator will be a three dimensions vector. The vectorial water allocation indicator aims to calculate the deviation of the water system accounting compared to the ideal scenario. The three vector components are consumptive uses $(VWAI^C)$, non-consumptive uses $(VWAI^{NC})$, and contamination for both uses $(VWAI^B)$. For the first vector component, the value can be positive or negative to differentiate if the uses are over-supplied or under-supplied; in the other two cases, the indicator value is always positive.

The consumptive uses vector component aims to represent the basin state and whether it has the necessary resources to satisfy all uses. The assessment is in the demand fulfillment for consumptive uses (C); a determined use can be under-supplied or over-supplied. For this kind of use, the objective is to fulfill 100% of the demand. The first step is calculating the percentual difference between the accounting system and the ideal scenario, as shown in Equation 3.12. Then it determines the deviation between this difference and the perfect case (when it is zero).

$$\Delta_i^C = \frac{WAS^Ci - IS_i^C}{IS_i^C}\,\forall i \in C \tag{3.12}$$

The sign depends on the basin's behavior and the importance of some uses over others. The sign in the value determines if the basin is under-supplied or over-supplied. If the basin is under-supplied, Δ_i^C is positive; if it is over-supplied, Δ_i^C is negative. For the formulation of this difference, we will assume that the sign determination depends on an importance scale formulated with four levels. The first level has uses considered more critical to the environment and humanity. Then, the second level has uses essential for humanity, but they have less priority than the first. The third level has uses essential for the national economy and development. Finally, the fourth level includes the rest of the uses. The values are between 1 and 0.5; the first level has a higher value, and the fourth level has a lower value. Table 3.1 shows the relative importance value of each level, following the uses hierarchy defined in this work. The column "Level" represents the hierarchy level of the uses, and the column "Value" the relative importance of the level.

Table 3.1: Importance scale for water consumptive uses.

Use	**Level**	**Value**
Domestic	1	1
Agricultural	2	0.84
Mining Industry	3	0.66
Livestock Production	4	0.5
Environmental protection	1	1

Level 1 contains domestic use and environmental protections. Domestic use is chosen as a priority because the objective is to ensure availability and sustainable water management, as defined in the sustainable development goals (UN) [71]. Environmental protection is at this level because it is necessary to preserve the ecosystems in the basin, represented through environmental flow, which aims to maintain components, functions, processes, and resilience of aquatic ecosystems giving goods and services to society.

Level 2 only contains agriculture because it is fundamental for people's survival, and it is necessary to have available resources for food production; hence, it has to be a high priority. Nevertheless, agriculture is the first water consumer at the global level; hence it is in level 2 because agriculture is necessary for human life and development, but its consumption needs to be regulated.

Level 3 is assigned to the mining industry due to its importance as the first economic activity of Chile, being the principal economic activity of gross domestic product (GDP) [72]. Finally, level 4 is livestock production because this work considers the activity with the most negligible impact on people and the country's economy (their contribution to GDP is just 0.57% [73]).

The sign value is calculated with a weighted sum between the difference ratio and ideal case with the importance (I) for each use (second column of Table 3.1), how is shown in Equation 3.13:

$$s = \frac{\sum_{i \in C} I_i \left(1 - \frac{WAS_i^C}{IS_i^C}\right)}{\sum_{i \in C} I_i} \tag{3.13}$$

The indicator value for consumptive use is[4]:

$$VWAI^{C} = sign(s) \cdot \sqrt{\frac{\sum_{i \in CU}(0 - \Delta_i^C)^2}{|C|}} \tag{3.14}$$

The mathematical expression represents a deviation between the real and the ideal case. If the result is between -1 and 1, it implies, for most of the uses, an under-supplied or over-supplied at most of 100% due to the average between the differences (Δ_i^C) being smaller than 1. If the value is smaller than -1 or higher than 1, the difference tends to be greater than 100%.

For non-consumptive uses (NC), the evaluation is in the water requirements difference. These uses utilize the water from rainfall or the basin; the objective is to compare the available water and the water used. This comparison is made using the deviation between the ideal (available water) and the current usage case. The first step is to calculate the percentage difference, then the indicator value, as shown in Equations 3.15 and 3.16, respectively.

$$\Delta_j^{NC} = \frac{WAS_j^{NC} - IS_j^{NC}}{IS_j^{NC}} \; \forall j \in NC \tag{3.15}$$

$$VWAI^{NC} = \sqrt{\frac{\sum\limits_{j \in NC}(0 - \Delta_j^{NC})^2}{|NC|}} \tag{3.16}$$

Similarly to consumptive use, if the result is between 0 and 1, it implies, for most uses, an under-supplied or over-supplied at most of 100% due to the average between the differences (Δ_j^{NC}) being smaller than 1. If the value is higher than 1, the difference tends to be greater than 100%. Nevertheless, unlike the consumptive uses, this component does not differentiate if the water flow has been in excess or insufficient for the service; it just gives the deviation. This configuration is adopted because, in Chile, these kinds of uses usually are oversupplied; hence the result is attributed to more extensive water use.

For mixed uses (B), the pollution produced by them or their processes is the evaluation basis. Unlike the other components, in this case, the comparison is made between a base case (grey WF in a determined year, previous to the assessment with enough data to do the comparison[5] and the current case, establishing a ratio of the amount reduced compared to the reference value, aiming to reduce pollution to a maximum. The calculation is performed using the deviation between the ideal case (when the rate is one) and the actual case. Hence, the reduced contamination percentage and the indicator value are calculated using Equations 3.17 and 3.18, respectively.

$$\Delta_k^B = IS_k^B - \frac{WAS_k^{B,b} - WAS_k^B}{WAS_k^{B,b}} \; \forall k \in B \tag{3.17}$$

---

[4] *sign()* means the value sign (±).

[5] The choice of the year is the user's decision.

$$VWAI^B = \sqrt{\frac{\sum_{k \in B}(0 - \Delta_k^B)^2}{|B|}} \tag{3.18}$$

In this case, the result indicates the average percentage reduction of current pollution regarding the base case of the uses. Then, the expected result will be between 0 and 1.

The proposed vector is three-dimensional, in which each value represents how far the current situation is from the ideal situation considered in this work. This vector can be represented in a polar or star plot, in which the radial distance on the 0° axis represents the value for non-consumptive use, the radial distance on the 180° axis represents the value for contamination for all uses, and the radial distance in the vertical axis represents the value for consumptive uses when it can be positive or negative.

Figure 3.11 shows an example of a basin not supplying the entire amount required by consumptive uses, not having an exact demand fulfillment for non-consumptive uses, and producing water pollution. The value for $VWAI^C$ is 0.326, then the basin does not entirely supply the consumptive uses, and the values are far, on average, 32,6% from the ideal case. In this case, the deviation value is high; hence it can be interpreted as significant basin overexploitation. $VWAI^{NC}$ value is near 0.491; hence, the values are far, on average, 49% from the ideal case. Finally, the value for $VWAI^B$ is 0.301, which implies a pollution reduction regarding the base case of 30%, on average, for the uses. As the ideal scenario considers no contamination, any positive value means a detriment to the basin ecosystem or the flow sink because some uses still contaminate.

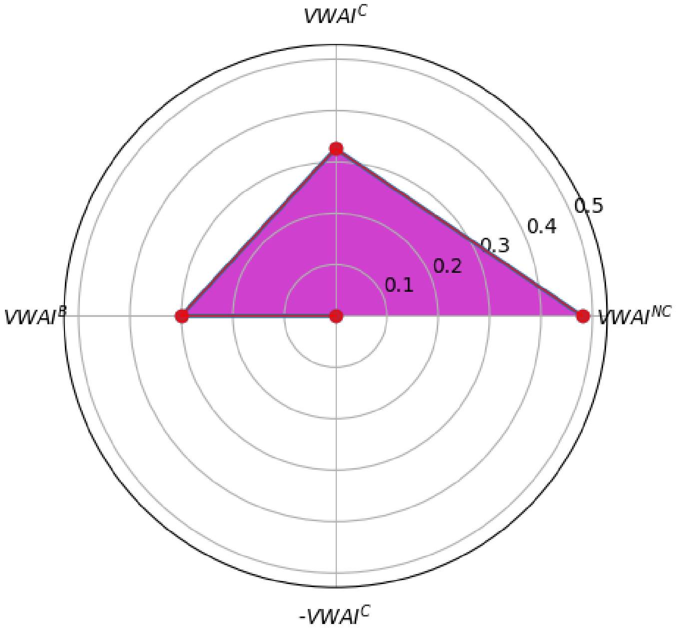


Figure 3.11: Vectorial indicator representation for a basin in which its current situation, regarding the demand fulfillment of uses, is far from the ideal scenario. In this case, the basin undersupplied its consumptive uses. The vectorial indicator result is VWAI = [0.326, 0.491, 0.301].

Figure 3.12 shows an example of a basin providing more water than necessary for consumptive uses, not having an exact demand fulfillment for non-consumptive services, and both produce water pollution. As the ideal scenario considers no contamination, any value means a detriment to the basin ecosystem or the sink of the flow. The value for $VWAI^C$ is around -0.5, then the basin supplies, on average for the uses, 50% more than the ideal case. In this case, the deviation value is high; then, it can interpret significant basin overexploitation. $VWAI^{NC}$ value is near 0.491; hence, most values ($\sim$ 68%) are farther at most 49% from the ideal case. Finally, the value for $VWAI^B$ is 0.301, which implies a pollution reduction regarding the base case of 30%, on average, for the uses.

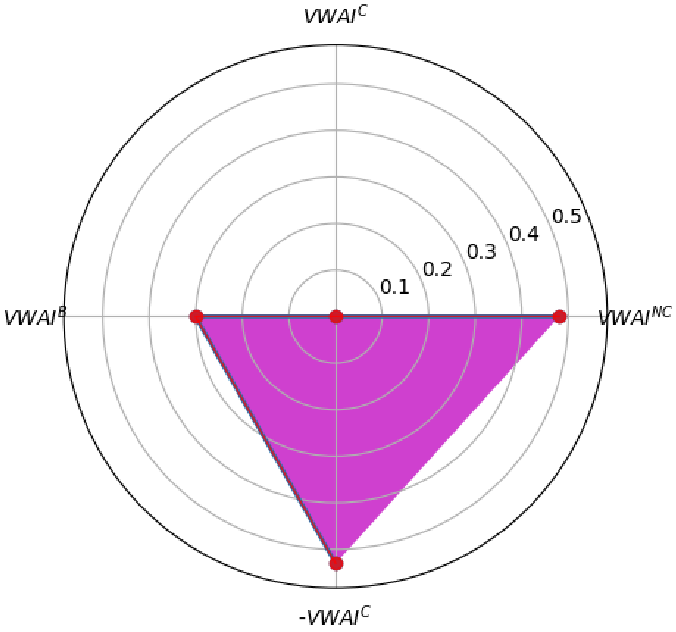


Figure 3.12: Vectorial indicator representation for a basin in which its current situation, regarding the demand fulfillment of uses, is far from the ideal scenario. In this case, the basin oversupplied its consumptive uses. The vectorial indicator result is VWAI = [-0.529, 0.491, 0.301].

3.3. Discussions

This chapter proposes a vectorial indicator to assess the water allocation in a basin. The assessment compares an ideal and real case for water consumption and pollution. The indicator results are a third-order vector and a polar graph.

The definition of an ideal scenario for the different uses is the assessment base for indicator creation. For each use, the definition is different depending on its properties and the factors affecting them. These ideal scenarios are an approach to the actual water requirements because it generalizes a year's consumption, a species group, and determined climate conditions, among other necessary assumptions depending on the case. These approximations can be an overestimation or underestimation of the requirement. However, considering the available data, it is closest to reality, and the estimation is approachable for any case.

The proposed indicator aims to show *how allocation should be*. Nevertheless, there is not a clear idea about *how should it be* because it is defined by social aspects and not only by humanity or nature. Each country defines its guidelines as shown in Section 1.2. Then, the indicator shows the difference between *what should be* and *what it is* depending on the country or allocation objectives. The deviation gives this relation, aiming to indicate the use distribution regarding each assessment. Hence, the number will represent, on average, how far it is from the ideal case. In the best case, each indicator component will be zero. For consumptive and non-consumptive uses, it means equality between the ideal and current case regarding water consumption. For pollution of mixed uses, it means no water pollution is introduced in the basin.

If some or all components are different from zero, it means a difference between ideal and observed cases. For consumptive uses (first component), the value can be positive or negative if the basin supplies less or more than the demand respectively. In the example of Figure 3.11, the value is 0.326; hence, the basin is undersupplying the uses, and the current and ideal scenario difference is 32.6%.

Regarding the structure of the indicator and the importance assigned to different uses, the first level has domestic and environmental protection uses because it prioritizes demand fulfillment of social and environmental necessities. We assigned domestic use this principal position because we consider people have the right to have enough water flow to supply their basic needs. Similarly, we assigned environmental protection first importance because we consider the basin to preserve its ecosystems' correct maintenance and development. The second level contains agricultural use because protecting people's food availability is necessary. Nevertheless, we did not assign it the first level due to the relative importance of primary water consumers (around 70%) worldwide and because we consider that it is essential to encourage technologies for progressive water consumption reduction in agriculture. The third level includes the mining industry due to its importance to the Chilean economy. However, other countries can differ depending on their economic resources, positioning it at a lower level due to the negative consequences it causes to the environment [74]. The fourth and last level includes livestock production because we consider it the least important factor to people, the environment, and the economy [75].

Regarding non-consumptive uses (the second component), the indicator component represents whether there is a difference between the ideal and real cases. In this case, it does not differentiate whether they are undersupplied or oversupplied because, in Chile, these kinds of uses usually are oversupplied; hence the result is always attributed to more extensive water use. The component value indicates the relative difference reached for the uses. In the Figure 3.11 example, the value is 0.491, which means a distance of around 49.1% from the current scenario to the ideal one.

In the pollution case, the indicator component does not measure the difference between an ideal and real scenario but between the base and real case. The base case is the accounting over pollution, given by WAS^P, in a determined year previous to the current one. Hence, the third component assesses the progress regarding decreases in water pollution. Like the other components, this calculation is performed through deviation. In the example of Figure 3.11, the value is 0.301, meaning the uses have decreased, on average, 30.1% their pollution between the current and the base case.

The demand fulfillment and water pollution measures have different objectives; then, the proposed vectorial indicator is required not to lose information about different assessments. In the case of consumptive and non-consumptive uses, it is also necessary to separate them because water utilization is different for each one. Non-consumptive uses can use rainfall water to return the water to the basin.

The water allocation problem is very complex since it depends on various aspects. Having a tool to summarize the basin status in a single number is difficult because the environmental, social, and economic assessments must be different. Currently, more water is required to supply the users' necessities; nevertheless, the problem is not associated with the resource, but to demand, which has been increasing over the years. Hence, it is necessary to consider all sustainability aspects to assess and determine the allocation, aiming to preserve water resources. The indicator created in this work is a starting point for the solution to the water scarcity problem. It assesses the basin status regarding water abstraction and pollution caused by each use. Even so, the indicator could be improved by distinguishing its advantages and disadvantages in the future. For example, the importance scale could be applied to all components and not just to consumptive uses.

The indicator summarizes the basin status for consumptive, non-consumptive, and pollution of mixed uses. Then, it has the advantage of being easy to understand and showing where the main basin problems are. The indicator mainly assesses the individual, community, and environmental aspects; however, as the water problem affects the three dimensions of sustainability, the indicator involves all of them, and its use also impacts all of them. Finally, the indicator is easy to apply because it needs two case scenarios for comparison, the current and the desired ones. The values are normalized to be a proportion between the ideal and current case, and each one aims to be zero, which would be the best-case scenario.

Chapter 4

Water tenure analysis

This Chapter introduces the water tenure concept. The first Section gives a general background and its difference with water rights. Then, the second Section defines the arrangement types existing in water tenure. Finally, the third Section related the water tenure with the vectorial indicator.

The water scarcity problem requires changes in understanding, using, and allocating water because it is a decreasing resource. The water tenure analysis is relevant because it involves an international perspective on future goals of water use and management. Then, as the indicator is a tool for the water tenure application, the relation between both is an advance for future updates in Chilean legislation and other countries.

4.1. Background: definition and importance of water tenure

Water Tenure is defined by Stephen Hodgson, as *the relationship, whether legally or customarily defined, between people, as individuals or groups, concerning water resources* [21]. Tenure gives an integrated understanding of these relations and helps to identify opportunities for defining better complex water uses. Besides, it regulates the abstraction of natural sources for drinking water purposes [21]. Nevertheless, this concept is not used by countries because it is in development, and currently, the concept used is *water rights.* The difference with water rights is considering the human right to water and taking care of claims to specific water resources, understanding the relationship with the environment and its necessities, and not just a source in specific.

Unlike tenure, a formal international definition of water rights does not exist. They are usually confused with the human right to water. Nevertheless, in general, water rights are understood as *a legal right to abstract and/or use a specific quantity of water contained in a natural source such as a river, stream, or aquifer. Water rights always apply concerning a specific water source* [76] then involves allocating the quantity. Besides, water rights have a problem because even if the law can determine them, it does not mean they exist in practice [21]. In contrast, water tenure analyzes the relationship between the use, importance, and flow amount utilized and if a specific use can cause social, environmental, and economic benefits and problems.

Another advantage of water tenure is improving water resources management and promoting environmental protection and conservation. From the legal side, it can vary between jurisdictions, even between basins. The focus is on the user, then it is not subject to specific or international laws, and each country or state is free to establish its politics [21].

Figure 4.1 shows how water tenure implies an integrated water assessment approach through the relation between the governance and accounting of water. Tenure aims to have a more efficient use and equitable allocation of water resources through control regimes, which monitor, control, and audit them because it concerns the accounting and environmental consequences caused by the utilization of water resources. Its application, in a real case, demonstrates how to grant access to use, control, and transfer rights of water resource benefits. Additionally, tenure regulates the responsibilities and restrictions of the water resources administrators, and beneficiaries [76].

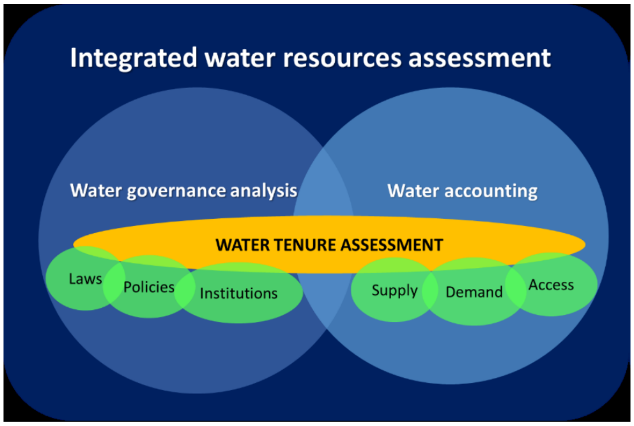


Figure 4.1: Importance of water tenure assessment for an integrated water resources assessment. Source: Food and Agriculture Organization of the United Nations. Reproduced with permission.

Finally, to define an effective water tenure system, it has to include the following values:

- Recognize the relationship between access to water resources and socioeconomic well-being.
- Define and ensure the conditions and rights of the water resources.
- Recognize the different water tenure forms.
- Allocate the rights to benefits of water resources use.
- Account water resources and their benefits.
- Ensure tenure security of water resources benefits.
- Provide data clarity about the access to water and have rules and protocols for conflict resolution.

4.2. Relation types of tenure arrangements

In water tenure, different arrangement types aim to regulate water abstraction from one source for drinking or other purposes. These agreements are essential for the states to have effective control to ensure the human right to water. The formal law can or not define the different tenure arrangement types. Inside official law are traditional formal water rights, modern formal water rights, regulatory licenses, control agencies, water supply contracts, commonhold water tenure, investment contracts, de minimis rights (small scale), exempt commercial uses, and reserves/minimum flow requirements. The relationships not defined by formal law are customary water tenure, religious law, informal water tenure, assumed rights, impossible rights, and unrecognized water tenure (revise Appendix B.1 for more information) [21].

The same water body can provide different user types; hence the tenure arrangement type depends on the water abstraction objective. Then, defining these kinds of uses according to social, economic, and environmental necessities becomes essential. Water tenure considers eight use types: domestic, agriculture, industry, hydropower, environment, navigation, inland fisheries/livelihoods, and recreation/landscape. Depending on the country and its governance, it considers one or more types [21].

Nevertheless, the nature of water makes it a fluid resource because water resources can not be defined as private ownership, unlike, for example, land [21]. Then there are many uses and tenure arrangements over the same resource. Figure 4.2 shows the overlapping of different uses and agreements in the same river.

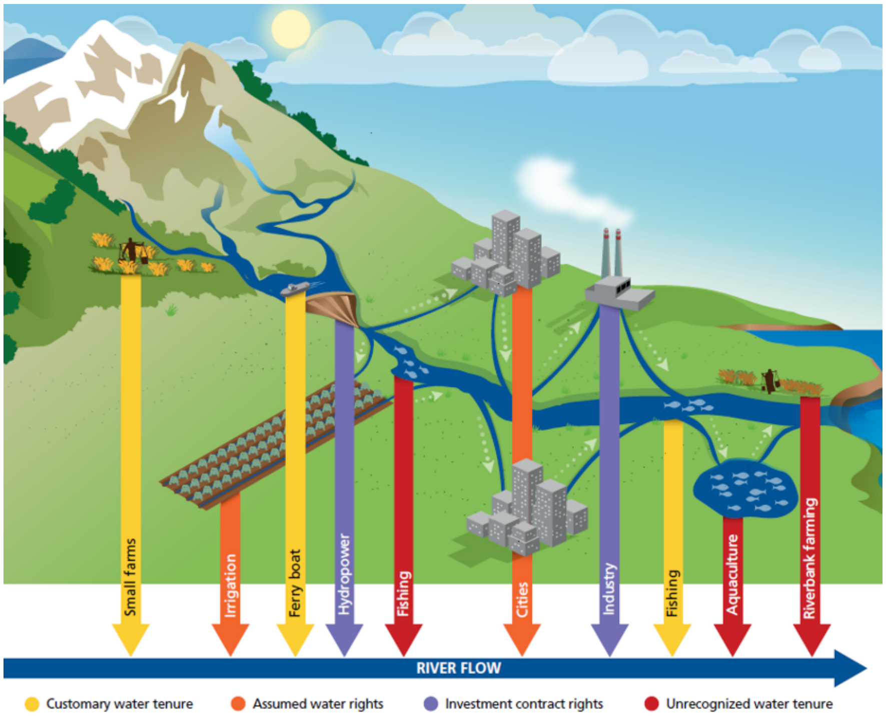


Figure 4.2: Diagram of water tenure where there are different uses and arrangements over the same flow in a river. Source: Food and Agriculture Organization of the United Nations. Reproduced with permission.

4.3. Relation between water tenure and the vectorial indicator

Tenure involves water use, accounting, inspection, and environmental consequences, which a determined use can generate; then, having a summarizing tool for the information is important. The vectorial indicator objective is to assess the water allocation in a basin, analyzing the available flow, the flow required for the different types of use, and their environmental consequences. At the same time, water tenure aims to have an integrated relationship between the water resources, their uses, and social, economic, and environmental consequences. Water tenure arrangements analyze the basin context because more than just allocating water is needed. The main goal is to know the purpose of this water, how it can be useful for society, its consequences, and why it is more important than others.

The vectorial indicator goal is to support the decision-making process for water allocation in a basin. Knowing the basin situation and requirements is necessary before allocating their flows and assessing if it can provide all the requests. Then, to improve water resources management, the analysis and hierarchy of the request based on economic, social, and environmental aspects, as water tenure does, is significant.

Figure 4.3 shows how the vectorial indicator and water tenure are related. The indicator assessment gives an approach to the basin state regarding the withdrawals associated with the uses (consumptive and non-consumptive) and the pollution caused by them. This information can be the base for understanding the relationship between the basin's environmental requirements and the uses supply needs. The result is a numeric value representing how far is the current context from the ideal, where each society defines the last one. For example, the indicator value of consumptive uses reports if they are under-supply or over-supply, then it gives an idea for the decision-making for the allocation regulation, aiming to be more equitable. The above relation also applies to non-consumptive uses. In the case of pollution for all uses, the value indicates the decrease in contamination regarding a base case. Nevertheless, while the result not being zero, some uses still harm the water resources, becoming necessary to analyze the allocation from this point of view.

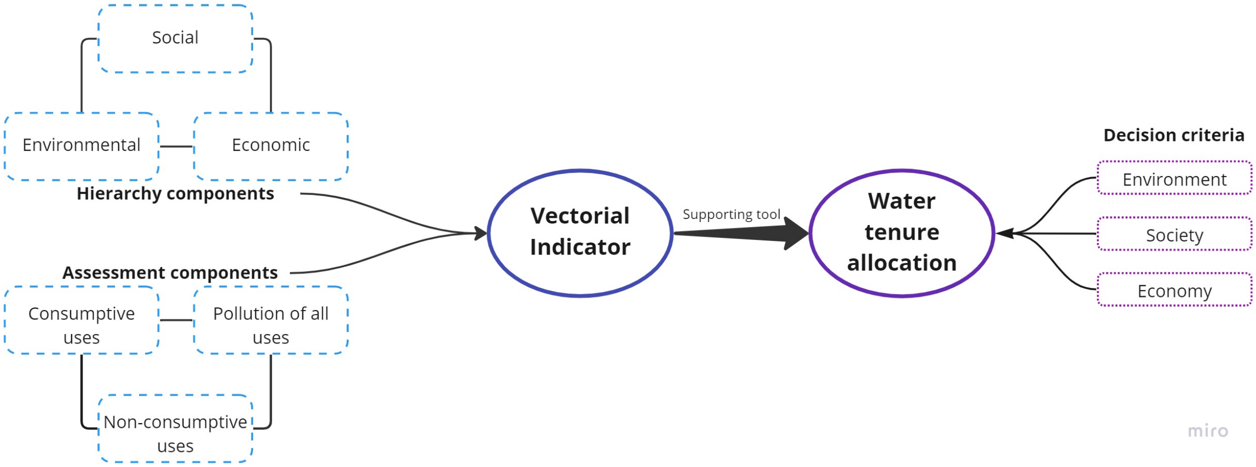


Figure 4.3: Graphic synthesis of the relation between the vectorial indicator and water tenure.

Chapter 5

Case study: the Tolten river basin, Chile

This Chapter utilizes a south basin of the country to test the Water System Accounting and the Vectorial Water Allocation Indicator. For this, first, there is a definition of the system parameters for the Chilean case and then determine all the basin variables of supply and demand. The choice of Tolten River Basin is because it is the second larger in the ninth region and supplies seven of the eight uses defined in this work. Then the following questions arise: *The Tolten river basin water has an equitable allocation? Is the current water allocation equitable?* To answer the questions, the Chapter has two goals: diagnose the current basin allocation and plan a better future allocation through an optimization problem.

5.1. Tolten river basin: defining an ideal scenario

The Rio Tolten basin is located in the Araucania region, the ninth region of Chile, and is the second largest region. Figure 5.1 shows its geographic location. It has a surface of 8,446 ha, the large of its main channel is 196 km [77], and its mean flow is 15.495 Mm^3/y [78][6] (see Appendix C.1). There are two climates types: warm rainy temperate with Mediterranean influence and cold rainy with Mediterranean influence [79]. Because there are four forest types and aquatic flora, the basin has more than fifty different species characteristic of the terrestrial flora basin [79]. Regarding the fauna, the benthic has mainly 18 different species, and the fish has mainly 17 different species, of which 14 are in a vulnerable situation or an extinction warning [79].

The basin has 30% of the region's water rights awarded, which most have not declared its use. Hence, the basin has to supply diverse water uses [77]. The main economic activity is tourism; nevertheless, agriculture, livestock production, forest industry, and aquaculture also are being developed [79].

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[6] Download basin data of *9437002 - Rio Tolten En Teodoro Schmidt*

Figure 5.1: Araucania region basins. Source: AMPHOS [80].

5.1.1. Consumptive uses

5.1.1.1. Domestic

The determination of population provided by the basin is through Censo 2017 data[7]. A population of 227,390 people is determined [82] (see Appendix C.2) belonging to Melipeuco, Cunco, Freire, Teodoro Schmidt, Curarrehue, Pucón, Pitrufquén, Toltén, Gorbea, Villarrica, and Loncoche communes [79].

The minimum water flow required for people for basic needs is 175 $[\frac{l}{d}]$ [63]. Then, the ideal scenario for the river Tolten basin corresponds to the annual demand for domestic use:

$$\begin{aligned} IS^{C}_{dom} &= P \cdot Qp \\ &= 14,525 \left[\frac{km^3}{y}\right] \end{aligned} \tag{5.1}$$

---

[7] Tool for accounting and knowing population, through the questions: how many and how are people, and where and how to live people [81]

5.1.1.2. Agriculture

The main crops in the ninth region of Chile are wheat (34.1 %), oatmeal (30 %), rape (9.7 %), triticale (5.5 %), potato (4.2 %), and lupine (3.2 %) [83]. Table 5.1 show the crop area and the mean crop factor for each one ($\bar{K_c}$) [84, 85]. The detail for all values is in Appendix C.4.

Table 5.1: Crops values

Crop	**Crop area** $[m^2]$	$\bar{K_c}$
Wheat	$9.11 \cdot 10^8$	0.85
Oatmeal	$8.03 \cdot 10^8$	0.83
Rape	$2.60 \cdot 10^8$	0.81
Triticale	$1.48 \cdot 10^8$	0.9
Potato	$1.11 \cdot 10^8$	0.96
Lupine	$8.58 \cdot 10^7$	0.9

To determine the Tolten river basin demand, the consideration of the basin having to supply 32.5% of the region (see Appendix C.3) is taken. Besides, the annual precipitation is 1,713 $[mm]$ [78], and the average efficiency for the irrigation system is 75% [86]. Then, the ideal scenario for the river Tolten basin is the annual demand for agriculture use:

$$\begin{aligned} IS_{ag}^{C} &= \frac{\left(\sum_{cr \in Cr} \bar{Kc}_{cr} \cdot ET_0 - Pe\right) Aag_{cr}}{\eta} \\ &= 14,647 \left[\frac{km^3}{y}\right] \end{aligned} \tag{5.2}$$

5.1.1.3. Mining industry

There is no development of the mining industry in the ninth region; hence this case study is not considered. For more information on the mining industry in Chile, see Appendix C.5.

$$IS_{min}^{C} = 0 \tag{5.3}$$

5.1.1.4. Livestock production

The main animals of livestock farming in the ninth region of Chile are beef cattle, sheep, and swine [87]. Table 5.2 show the animal's quantity and how much water requires each one per day [88–90].

Table 5.2: Livestock values

Livestock	**Quantity** $[an]$	**Water requirement** $[\frac{l}{an-d}]$
Beef cattle	479,438	51.5
Sheep	208,646	2.24
Swine	177,451	15

To determine the Tolten river basin demand, the consideration of the basin having to supply 32.5% of the region (see Appendix C.3) is taken. The ideal scenario for the river Tolten basin is the annual demand for livestock production use:

$$\begin{aligned} IS_{lp}^{C} &= \sum_{a \in A} a_a \cdot na_a \\ &= 3,300 \left[\frac{km^3}{y}\right] \end{aligned} \tag{5.4}$$

5.1.1.5. Environmental protection

The Tolten river basin studies of requirements and protection determined the ecological flow has to be 105 $[\frac{m^3}{s}]$ [91].

$$IS_{ep}^{C} = 3,311,280 \left[\frac{km^3}{y}\right] \tag{5.5}$$

5.1.2. Non-consumptive uses

5.1.2.1. Forest industry

The precipitation determination of the Tolten river basin is through the average calculus of annual precipitations between 2016 and 2019 [78].

In Chile, the dominant forest plantations types are Radiata pine and Eucalyptus, having a 56% and 36.8% of the total surface, respectively [92]. Besides, in the Araucania region, there is 20,7% of the country equal to 632,289 *ha* [93][8]. Similarly to the livestock production case, to determine the Tolten river basin demand, the consideration of the basin having to supply 32.5% of the region (see Appendix C.3) is taken. The ideal scenario for the river Tolten basin for forest industry use will be:

$$\begin{aligned} IS_{for}^{NC} &= Pa \cdot Afor \\ &= 3,521,121 \left[\frac{km^3}{y}\right] \end{aligned} \tag{5.6}$$

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[8] Download document *Superficies de uso de suelo regional (actualizado a Julio 2021)*

5.1.2.2. Hydropower

The Tolten river basin has a distinguished hydropower potential contributing between 7% and 9% to the country, with a capacity of 811.72 $[MW]$ [94]. The flow would have to return hydropower central to the basin is [61]:

$$\begin{aligned} IS_{hp}^{NC} &= Qw \\ &= 21,667 \left[\frac{km^3}{y}\right] \end{aligned} \tag{5.7}$$

5.1.2.3. Aquaculture

In Chile, aquaculture is mainly developed for fish and bivalves hatchery [95]. The main fish species are Atlantic salmon and Coho salmon, and for bivalves is Chilean mussel [95]. In the case of bivalves is not considered due to its hatchery using seawater [96].

In the Araucania region, the estimated fish production is 418.61 $[t]$, in which 96.5% correspond to salmon [97][9]. For the basin, the model considered a production corresponding to 32.5% of the region. The maximum water flow necessary for salmon farming in Flow-Through systems is 2.4 $[\frac{l}{kg-min}]$ [98].

$$\begin{aligned} IS_{aq}^{NC} &= \sum_{f \in F} q_f \cdot M_f \\ &= 171,616 \left[\frac{km^3}{y}\right] \end{aligned} \tag{5.8}$$

5.1.2.4. Pollution for all uses

As was defined in Section 3.1.3, the ideal case for pollution is zero for all uses (U):

$$IS_k^B = 0 \,\forall k \in B \tag{5.9}$$

5.2. Accounting system for the Tolten river

The Water System Accounting defined in Section 1.3 is implemented in the Tolten river basin. Using national records studies [61, 99], and the ratio between the basin and the region determined in Appendix C.3, the results are present in Tables 5.3, 5.4, and 5.5, for consumptive uses, non-consumptive uses, and pollution for all uses, respectively.

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[9] Download document *Cosechas Centros de Cultivo Región* in section *Anuarios Estadísticos 2017*.

Table 5.3: Water withdrawals in Water System Accounting

Use	**Water withdrawals** $[\frac{km^3}{y}]$
Domestic	8,617
Agriculture	18,005
Mining industry	-
Livestock production	2,026
Environmental protection	2,515,627

Table 5.4: Non-consumptive demand in Water System Accounting

Use	**Non-consumptive demand** $[\frac{km^3}{y}]$
Forest industry	3,473,098
Hydropower	876,452
Aquaculture	25,717,796

Table 5.5: Pollution in Water System Accounting

Use	**Grey WF** $[\frac{km^3}{y}]$
Domestic	56,406
Agriculture	137,525
Mining industry	-
Livestock production	0.299
Environmental protection	0
Forest industry	9,061
Hydropower	0
Aquaculture	22.58

The assessment of the basin allocation is with VWAI calculus, and the results are shown in Table 5.6 and Figure 5.2. Through the image, only a problem with non-consumptive uses can be seen. Still, according to numeric results, consumptive uses and pollution differ from their ideal case. In the case of consumptive uses, the basin is mainly not supplying their demand. The value indicates the no fulfillment is, on average, 30%. The non-consumptive services have a higher difference between the ideal and current cases. The indicator value shows more than a 1,000% average difference, representing a severe problem for the basin and its regulation. Finally, the third component value indicates the pollution reduction of water regarding the base case is around 30%; then, there is a considerable contamination water reduction.

Table 5.6: VWAI results for Tolten river basin.

	$VWAI^C$	$VWAI^{NC}$	$VWAI^B$
	Consumptive	*Non-Consumptive*	*Pollution*
VWAI	0.326	85.94	0.301

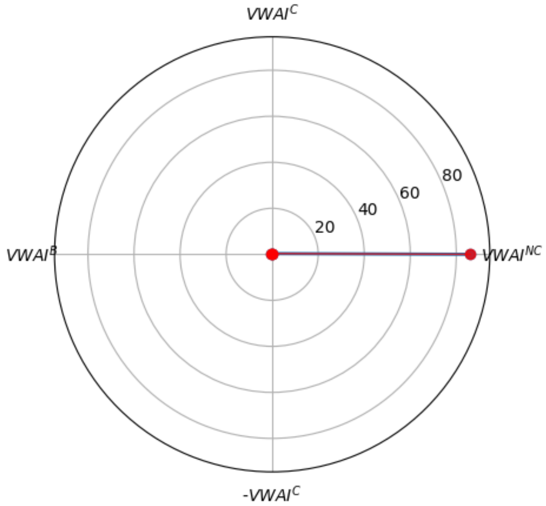

Figure 5.2: VWAI results for Tolten river basin.

The Figure's importance is to show how the result of the non-consumptive use hides the other two. The graph only distinguished one line because of the high difference between the numbers; nevertheless, $VWAI^C$ and $VWAI^B$ are not in the ideal scenario. This result is a particular case because, for example, in Figures 3.11 and 3.12, there is a clear representation of the results in the graph, and it is possible to distinguish the values.

5.3. Optimization problem: finding an equitable allocation

This Section aims to demonstrate how the indicator can be used as the objective function in an optimization problem, to facilitate the water allocation plan in a basin. The problem's purpose is to reach the ideal values for each indicator component, considering the basin's social, economic, and environmental needs and the area.

Optimization is a tool increasingly used in chemical engineering due to its impact on the industry, with principal applications in design and synthesis, operations, and control [100]. For instance, it has applications in solving water allocation problems in a basin for agriculture and domestic use [18, 42], the design of a bioethanol supply chain [101], and the design of an optimal water network in a region considering supply and treatment [102–106]. Some of these research and models [18, 42] describe water allocation for a specific use or industry. Still, no models describe allocation for all possible basin water uses.

A general structure of an optimization model (see Eq. 5.10) is composed of an objective function ($F(x, y) \in \mathbb{R}$), the decision variables ($x \in \Omega$), which can been continuous ($x \in \mathbb{R}^n$) or integers ($y \in \mathbb{Z}^m$), and the constraints ($g(x, y) \leq 0$; $h(x, y) = 0$). These three elements model and give an improved solution for the problem. The classification of an optimization problem and how it is solved depends on its formulation, if it is a linear or non-linear problem, and if its variables are discrete or continuous. Hence the main cases are Linear Programming (LP), Non-Linear Programming (NLP), Mixed-Integer Linear Programming (MILP), and Mixed-Integer Non-Linear Programming (MINLP). The NLP and MINLP usually are about process design problems, and the LP and MILP problems of scheduling and planning [100]. Table 5.7 detailed the kind of problem in the industry and which solution is used based on its formulation.

$$\min F(x, y) \text{ s.t. } \begin{cases} h(x, y) = 0 \\ g(x, y) \leq 0 \\ x \in \mathbb{R}^n \\ y \in \mathbb{Z}^m \end{cases} \tag{5.10}$$

Table 5.7: Formulation of optimization problems in process systems engineering [100].

	LP	**MILP**	**NLP**	**MINLP**
Process Design and Synthesis				
Heat Exchangers	★	★	★	★
Mass Exchangers	★	★	★	★
Separations	-	★	★	★
Reactors	★	-	★	★
Flowsheeting	-	-	★	★
Process Operation				
Scheduling	★	★	-	★
Supply Chain	★	★	-	★
Real-Time Optimization	★	-	★	-
Process Control				
Model Predictive Control (MPC)	★	-	-	-
Nonlinear MPC	-	-	★	-
Hybrid MPC	-	★	★	★

5.3.1. Model

The present work aims to find the best water allocation in the Tolten river basin. A NLP optimization model represents this problem, in which the main constraints are not exceeding the basin capacity and meeting each water use's demand. Figure 5.3 shows an overview of the model, including its inputs, outputs, constraints, and objective function.

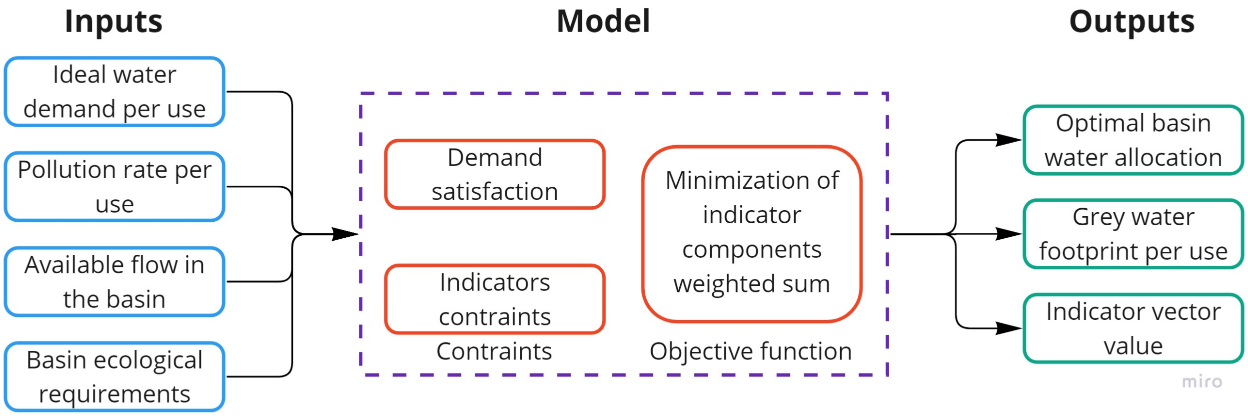

Figure 5.3: An overview of the optimization model.

For the development of the problem, the basin will provide all the water demand, and the basin has to have a reserved flow to comply with water requirements for consumptive and non-consumptive uses, respectively. Besides, the model construction uses the water accounting systems and the vectorial indicator created in this work. It aims to minimize the weighted sum of the indicators, obtaining an optimal solution. In the case of the first indicator component, it is considered its absolute value.

The model inputs are the available flow to allocate, the pollution rate per flow, the ideal water demand for each use, and the ecological requirements of the basin to maintain all its ecosystems. Meanwhile, the outputs obtained are the optimal basin water allocation, with the flow values for each use, the grey WF generated by each use, and the vectorial indicator values.

The description and explication of the optimization model are in detail in the following sections: the superstructure, the constraints, and mathematical expressions, the objective function, the sets, variables, and data used as input parameters. Section 5.3.2 shows the outputs and results of the model. Besides, in Section 5.3.3, the problem is solved in a future scenario considering a decrease in basin capacity and an increase in water demands.

5.3.1.1. Superstructure

Figure 5.4 shows the superstructure of the allocation problem for all uses: consumptives and non-consumptives. The system includes the pollution produced by the uses, measured in terms of greywater footprint. The water polluted after being utilized goes to the same or different water source, represented by the Sink.

The problem through the vectorial indicator defined in Chapter 3 is optimized. The objective is to minimize their sum and reach the best result, given that the closer zero is the indicator, the better allocation is.

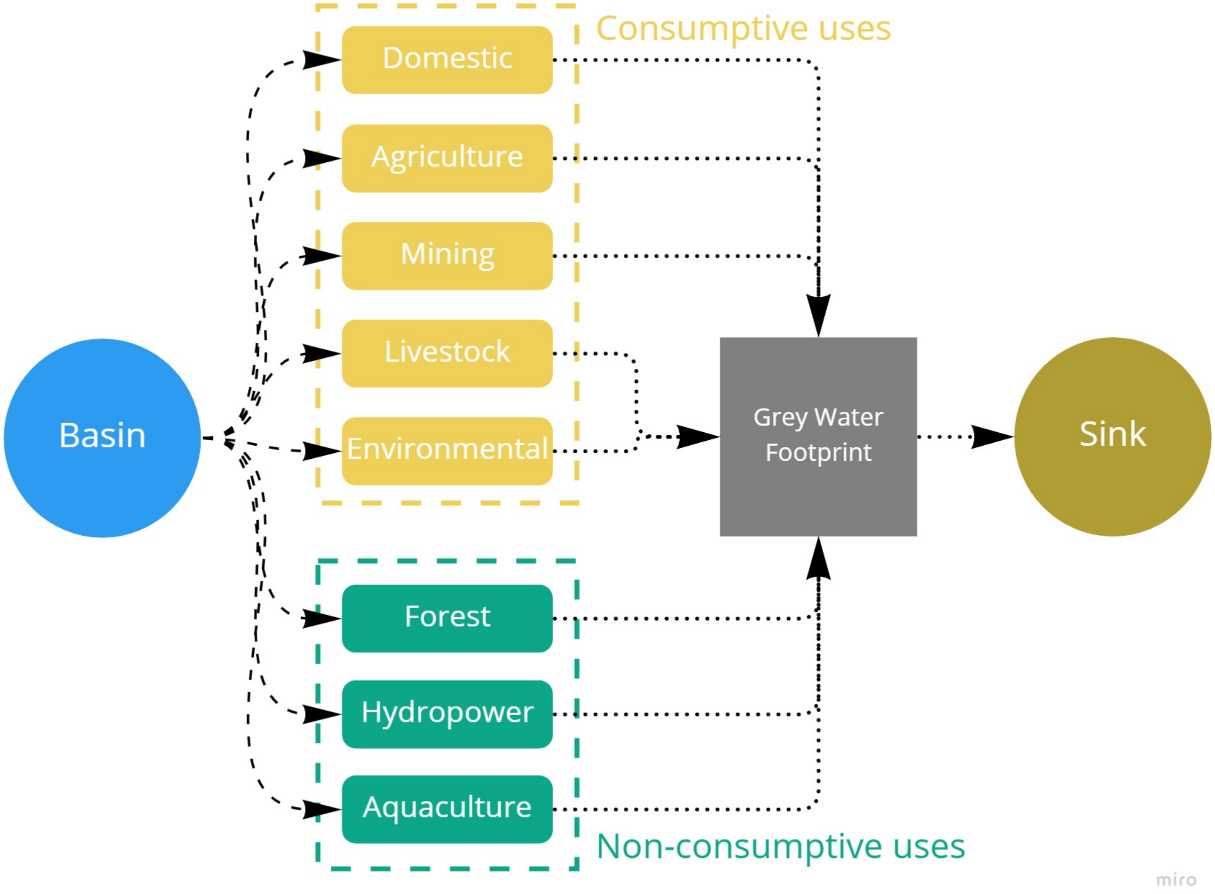

Figure 5.4: Superstructure of the model.

5.3.1.2. Sets

This section is defined the necessary sets to model the problem.

- CU : Set of consumptive water uses domestic, agriculture, mining industry, livestock production, environmental protection.

$$CU \;=\; [dom, ag, min, lp, ep]$$

- NCU : Set of non-consumptive water uses forest industry, hydropower, aquaculture.

$$NCU \;=\; [for, hp, aq]$$

- AU : Set of both water uses (the union of the above sets).

$$AU = CU \cup NCU$$

- I : Set of indicators.

$$I = [C, NC, P]$$

- $Crop$: Set of crops type in agriculture water use.

$$Crop = [\text{wheat}, \text{oatmeal}, \text{rape}, \text{triticale}, \text{potato}, \text{lupine}]$$

- An : Set of animals in livestock production.

$$An = [\text{beef cattle}, \text{sheep}, \text{swine}, \text{lupine}]$$

5.3.1.3. Parameters

This section defines the parameters used in the problem.

- $perc$: Percentage of Tolten river basin in Araucania region. This number represents the rate of water use by the Tolten river basin regarding all water use in the Araucania region. For more information, see Appendix C.3.
- q_{avail}: Flow available of Tolten river basin to be used $[\frac{km^3}{y}]$.
- qid_{au}: Ideal demand or ideal requirement of water by use $au \in AU$ $[\frac{km^3}{y}]$.
- q_{idp}: Ideal domestic flow per person $[\frac{km^3}{y}]$.
- Pop: Population supplied by the basin.
- qid_{dom}: Ideal domestic water demand $[\frac{km^3}{y}]$.

$$qid_{dom} = q_{idp} \cdot Pop$$

- η: Irrigation average efficiency.
- Pe: Precipitations coefficient $[\frac{mm}{y}]$.
- ET_0: Zone's evapotranspiration $[\frac{mm}{y}]$.
- Kc_c: Crop coefficient of crop $c \in Crop$.
- sf_c: Surface of crop $c \in Crop$ $[m^2]$.
- qid_{ag}: Ideal agriculture water demand $[\frac{km^3}{y}]$.

$$qid_{ag} = \sum_{c \in Crop} (Kc_c ET_0 - Pe) surf_c$$

- qid_{min}: Ideal mining water demand $[\frac{km^3}{y}]$.
- wrL_a: Water requirements per animal of specie $a \in An$ $[\frac{km^3}{y}]$.
- nAn_a: Animal number of specie $a \in An$ $[\frac{km^3}{y}]$.

- qid_{lp}: Ideal livestock production water demand $[\frac{km^3}{y}]$.

$$qid_{lp} = perc \sum_{a \in An} wrL_a \cdot nAn_a$$

- qid_{ep}: Ideal environmental protection water demand $[\frac{km^3}{y}]$.
- Pp: Annual precipitations $[\frac{mm}{y}]$.
- $Afor$: Forest area supplied by basin $[m^2]$.
- qid_{for}: Ideal forest industry water requirement $[\frac{km^3}{y}]$.

$$qid_{for} = perc \cdot Afor \cdot Pp$$

- qid_{hp}: Ideal hydropower water requirement $[\frac{km^3}{y}]$.
- $mSal$: Salmon average mass $[kg]$.
- $wrSal$: Salmon water requirements $[\frac{km^3}{kg-y}]$.
- qid_{aq}: Ideal aquaculture water requirement $[\frac{km^3}{y}]$.

$$qid_{aq} = perc \cdot wrSal \cdot mSal$$

- fg_{au} : Constant of pollution rate of use $au \in AU$.
- wfB_{au} : Grey WF in the base case for use $au \in AU$.

5.3.1.4. Variables

This section defines the necessary variables to model the problem.

- q_{au}: Water flow by use $au \in AU$ $[\frac{km^3}{y}]$.
- gWF_{au}: Grey WF by use $au \in AU$ $[\frac{km^3}{y}]$.
- $\Delta 1_c$: Ratio for consumptive indicator regarding ideal case of use $c \in CU$.
- $N1i$: Variance of $VWAI^C$ regarding zero.
- $\Delta 2_n$: Ratio for non-consumptive indicator regarding ideal case of use $n \in NCU$.
- $N2j$: Variance of $VWAI^{NC}$ regarding zero.
- $\Delta 3_{au}$: Difference for pollution indicator, between ideal case and use $au \in AU$ regarding all uses $n \in NCU$.
- $N3k$: Variance of $VWAI^B$ regarding zero.
- Ind_i: Value of indicator component $i \in I$.

5.3.1.5. Constraints and mathematical expressions

This section defines the necessary constraints and mathematical expressions to model the problem.

- The total water uses demand must not exceed the basin capacity:

$$\sum_{au \in AU} q_{au} \leq q_{avail} \tag{5.11}$$

- Fulfillment of the demand for each use $au \in AU$:

$$q_{au} \geq qid_{au}, \forall au \in AU \tag{5.12}$$

- Pollution occasioned by each use $au \in AU$:

$$fg_{au} q_{au} = gWF_{au}, \forall au \in AU \tag{5.13}$$

- Definition of difference ratio regarding ideal case for each consumptive use:

$$\Delta 1_c = \frac{q_c - qid_c}{qid_c}, \forall c \in CU \tag{5.14}$$

- Definition of variance of consumptive uses:

$$N1i = \frac{\sum_{c \in CU} (0 - \Delta 1_c)^2}{|CU|} \tag{5.15}$$

- Definition of $VWAI^C$:

$$Ind_C = \sqrt{N1i} \tag{5.16}$$

- Definition of difference ratio regarding ideal case for each non-consumptive use:

$$\Delta 2_n = \frac{q_n - qid_n}{qid_n}, \forall n \in NCU \tag{5.17}$$

- Definition of variance of non-consumptive uses:

$$N2j = \frac{\sum_{n \in NCU} (0 - \Delta 2_n)^2}{|NCU|} \tag{5.18}$$

- Definition of $VWAI^{NC}$:

$$Ind_{NC} = \sqrt{N2j} \tag{5.19}$$

- Definition of pollution progress regarding base case for each use:

$$\Delta 3_{au} = 1 - \frac{wfB_{au} - gWF_{au}}{wfB_{au}} \tag{5.20}$$

- Definition of pollution variance of all uses:

$$N3k = \frac{\sum_{au \in AU} (0 - \Delta 3_{au})^2}{|AU|} \tag{5.21}$$

- Definition of $VWAI^B$:

$$Ind_P = \sqrt{N3k} \tag{5.22}$$

5.3.1.6. Objective function

The vectorial indicator represents the data dispersion regarding each ideal case for consumptive, non-consumptive, and both uses. The objective is to minimize the weighted sum of the vectorial indicator components with relative importance for each. The definition of the variables is in $\mathbb{R}^+$; then, their minimization aims to be zero.

The values for relative importance are 1 for consumptive uses and 0.5 for non-consumptive uses. The value for the first ones is higher because they have more information than the second. In the case of pollution for all use, the model formulation and the grey WF definition make it impossible for this indicator to take the zero value because there will always be pollution associated with some uses. Hence, the pollution value does not predominate over demand fulfillment, and its importance is half of the non-consumptive uses.

$$Ind_C + 0.5 Ind_{NC} + 0.25 Ind_P \tag{5.23}$$

5.3.2. Results

This section presents the results obtained for the current scenario optimization. The implementation of the model in Julia is in Appendix D.

Figure 5.5 and Tables 5.8 and 5.9 show the optimization problem results for the vectorial indicator and flow and grey WF, respectively. All results flows are equal to ideal flows because the available basin flow is higher than the flow demand of both uses, then the basin can fully supply each water requirement. Hence, the indicator values are smaller than the current situation (see Table 5.6 and Figure 5.2). $VWAI^C$ and $VWAI^{NC}$ values are near zero but not equal to zero because of computational errors. In the case of $VWAI^B$ value, it can not be zero while there is an existent flow. In this problem, the calculus for grey WF is through a constant of pollution rate, then just one flow with the constant different to zero is enough to there will be grey WF and, thus, a value bigger than zero for $VWAI^B$.

Table 5.8: Vectorial indicator results

$VWAI^C$	$VWAI^{NC}$	$VWAI^B$
$2.165 \cdot 10^{-7}$	$4.441 \cdot 10^{-6}$	0.360

Table 5.9: Results of water allocation and grey WF by use.

	Ideal flow $\left[\frac{km^3}{y}\right]$	**Real flow** $\left[\frac{km^3}{y}\right]$	**Grey WF** $\left[\frac{km^3}{y}\right]$
Consumptive uses			
Domestic	14,525	14,525	111,873
Agriculture	14,647	14,647	1,055
Mining industry	0	0	0
Livestock production	3,300	3,300	0.487
Environmental protection	$3.31 \cdot 10^6$	$3.31 \cdot 10^6$	0
Non-consumptive uses			
Forest industry	$3.52 \cdot 10^6$	$3.52 \cdot 10^6$	9,186
Hydropower	876,452	876,452	0
Aquaculture	171,616	171,616	0.151

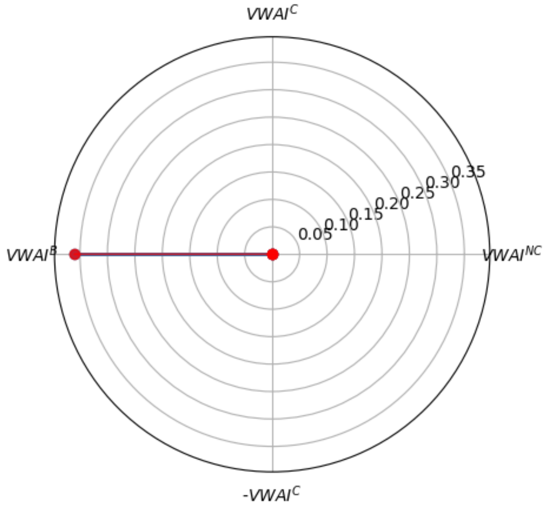

Figure 5.5: Graphic VWAI results for the optimized model in Tolten river basin.

5.3.3. Future scenario

The basin's future scenario is analyzed to use the vectorial indicator in a complex situation. Researchers expect a decrease in the monthly streamflows for 2040–2070. The worst case will be in summer, with a decrease of 19% ± 6%, and the better case in autumn, with 18% ± 9% [107]. Hence, for this study, the available basin flow will be the current flow reduced by 25%, corresponding to the summer worst scenario. Besides, the total water demand will increase over the years, and it can even double by 2050 [108]. The new demand or water requirement (i.e., ideal case) for each use, except environmental protection, is double than current. Although it considers a reduction in the basin streamflow, the flow for environmental protection will not change because the water requirement is not proportional to the volume depending on the basin ecosystems. For more detail, revise Appendix C.6

The optimization model utilized in this section is the same one used in Section 5.3.1. Nevertheless, the total water requirements are higher than the flow available, then to avoid infeasibilities in the problem, Equation 5.12 changes to:

$$q_{au} \leq qid_{au},\ \forall au \in AU \tag{5.24}$$

5.3.4. Results

This section presents the results obtained for future scenario optimization. The model implementation in Julia is in Appendix D.

The results obtained for the future scenario, using the same model defined previously and still not considering mining activity, are shown in Tables 5.10 and 5.11 and Figure 5.6.

Table 5.10: Vectorial indicator results for the future model.

$VWAI^C$	$VWAI^{NC}$	$VWAI^B$
0.459	0.026	0.733

Table 5.11: Future model results: water allocation and grey WF by use.

	Ideal flow $\left[\frac{km^3}{y}\right]$	**Real flow** $\left[\frac{km^3}{y}\right]$	**Grey WF** $\left[\frac{km^3}{y}\right]$
Consumptive uses			
Domestic	29,049	25,678	168,088
Agriculture	442,612	53,717	410,289
Mining	0	0	0
Livestock production	6,600	6,143	0.907
Environmental protection	$3.31 \cdot 10^6$	$2.55 \cdot 10^6$	0
Non-consumptive uses			
Forest industry	$5.99 \cdot 10^6$	$5.73 \cdot 10^6$	14,947
Hydropower	$1.75 \cdot 10^6$	$1.73 \cdot 10^6$	0
Aquaculture	343,233	342,412	0.301

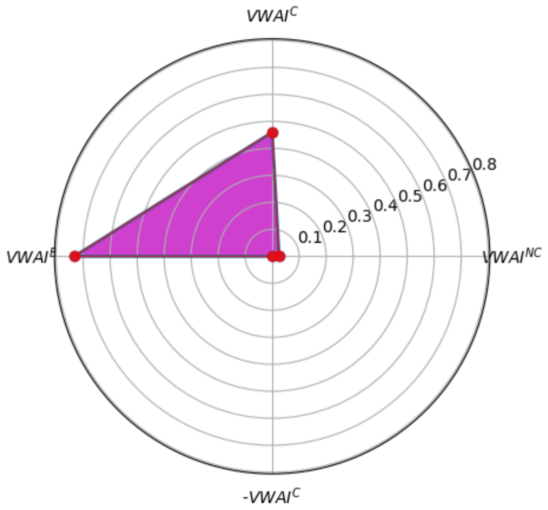

Figure 5.6: Graphic VWAI results for the optimized future model in Tolten river basin.

5.4. Discussions

This chapter presents an optimization problem trying the vectorial indicator in a real case. Tolten river basin is chosen due to the multiple uses to supply, and it defines its ideal scenario. It solves two optimization problems, one with the current context and data and the other in a future scenario, considering an increase in each use demand and a decrease in the basin flow.

5.4.1. Ideal scenario definition

Defining the ideal scenario follows the methodology presented in Section 3.1. The demand estimation uses governmental and bibliographic information to determine the main parameters in each use. It can generally obtain data close to reality for scenario creation, except for hydropower. In the case of this use, there is no data about the industries and their respective flows, then the value used corresponds to registered data of past demand. Although this consideration can overestimate the value, it ensures the assessment shows if the current industries overuse water in the future.

In the case of agriculture and forest use, it uses an annual average for rainfall data, which is variable and can have significant changes due to climate change. Hence, this assumption can underestimate or overestimate the value according to the case. Even so, it is a good approach for calculus and is not so far from reality because it is the precipitations in the basin and not in the region or country, for example.

Another case is livestock production and agriculture use due to take a general value for animal water requirement and crop factor, respectively. This approximation can differ from reality, but it is a reasonable approach to estimating water demand given that there is no specific information about the growing state of animals and crops in each case.

Generally, all values are approximations, but they are defined to make a realistic approach then the assessment will be the more accurate possible.

5.4.2. Current scenario

Two main constraints define the optimization model, one restricts the withdrawal flow to basin capacity, and the other requires demand fulfillment. These constraints give the boundaries to the vectorial indicator; then, its minimization respects the basin properties. The other constraints are mathematical expressions for the grey WF definition and the needed equations to define the vectorial indicator.

If the data is analyzed, it shows a flow available higher than the flow demanded, then the result is the same as expected. Because the condition of each use has to fulfill its demand, the problem allocates as a solution a flow equal to demand, obtaining the optimal values for $VWAI^C$ and $VWAI^{NC}$.

In the case of $VWAI^B$, this value can not be zero due to its calculus being from a pollution rate, which depends on the flow. Through the past grey WF record, it estimates the pollution rate for each use and assumes a proportionality with the flow consumed. This approximation is because there needs to be more information about methodologies to calculate grey water footprint or pollution caused by each use. Nevertheless, consider that the higher the flow utilized, the higher will be the contamination caused is realistic. The relation may not be strictly linear but maintains a direct proportionality to determine a pollution rate.

Regarding the objective function definition, it uses weights to indicator components, given the higher value to $VWAI^C$ and the minor to $VWAI^B$. The choosing of these values is, first, because the consumptive uses have more information than non-consumptive. After all, there are five in the first one and three in the second. Hence, to equal the assessments' importance and for both to have the same demand fulfillment possibilities, the $VWAI^{NC}$ weighs half of $VWAI^C$. Then, a still minor weight election for $VWAI^B$ is because this value can not be zero, while the others can. To not prioritize the contamination reduction above the demand fulfillment, its value is decreased to half of $VWAI^{NC}$.

For the current situation, the obtained results show an over-exploitation in the basin, and the optimization problem result shows that reducing the basin withdrawal flows is possible. This result provides more information about water utilization and how to start caring for the resource. Nevertheless, the $VWAI^B$ value increases from 0.301 to 0.360, meaning water pollution increases. This result is because the flows which decrease may not cause significant pollution, but the impact of uses that increase their demand flow is more significant and harmful to water quality. The form in what calculated grey WF causes an inverse effect with the flow; if the flow rises, the grey WF is also. Hence, if there are changes in the pollution rate, these are not considered the problem.

Based on the above, the main result is the $VWAI^B$ value due to the others reaching their optimal values. The contaminated flow can go to the same basin or other water body;

nevertheless, in any case, it is essential to improve the water quality and have a less possible impact. Hence, at this moment, the basin management's focus must be to reduce the pollution caused by uses.

To answer the initial question: *The Tolten river basin water has a correct allocation? Is the current water allocation equitable?* The need to compare the model results with the actual situation arises. The model reduces some uses showing that water is overused in the present, especially in non-consumptive uses, and it increases others due to insufficient supply. Besides, the allocation flows results from the model increase the $VWAI^B$ value regarding the current value because the uses that increase their flow are most polluting. Although not all vector components have the same behavior by optimizing the basin allocation, there is an improvement in the water allocation.

In conclusion, the current allocation is incorrect because some uses use more water than they need. While the basin has more water than required, the situation is sustainable. However, once there is less water, there will be an imbalance in the flows utilized by the uses, producing an unequal allocation.

5.4.3. Future scenario

Unlike the first problem, in this scenario, the available flow is less than the demanded flow, then the optimization problem is based on making decisions based on the indicator and the best combination of its components.

In this case, the vectorial results show an increase in the values regarding the current case optimization. The $VWAI^C$ value ascends to 0.459; hence there is a lack of supply for consumptive uses. The values of Table 5.11 show the main problem is in agricultural use because the supply is barely 12%; meanwhile, the other uses are over 75%. The big difference in the numbers is due to the high water pollution caused by agricultural use. Although it is the least supplied proportionally, it has the higher grey WF of all uses; then, the problem is a balance between the supply and the pollution.

Even though the $VWAI^{NC}$ value increases to 0.026, still been a small value; so, the non-consumptive uses mostly supply their requirements. In this case, the pollution they caused is much smaller than consumptive, so the problem prioritized first supplying these kinds of use.

The $VWAI^B$ value increases to 0.733, which means the progress in the pollution reduction decreases regarding the current case optimization and is closer to the base case. The main reason is the increase in demand; hence, to fulfill the demand, the water flows also have to increase. The grey WF estimation is through a direct proportion to the flow utilized. Nevertheless, it does not consider possible future technological advances to improve the water quality of output flows; hence the grey WF estimation might not be so accurate.

The obtained values show a significant problem in the supply of consumptive uses, giving a star point to analyze the basin situation and could make the allocation more equitable. The value of the pollution component indicates a low advance in efforts to decrease water contamination from industries and services regarding the base and current case. Nevertheless, the increase in pollution component value is because the demand flows increase, then what is explained in Section 5.4.2 happens. Still, the results show the necessity of stricter quality regulations to care for water resources.

The optimization model is efficient concerning allocation using all available flow. Still, it needs to consider the supply importance of some uses over others. It just tries to achieve the demand with the least possible pollution; then, the model prioritizes supplying the uses with the lower grey WF.

Finally, the vectorial indicator can support the allocation of water flows for each use, making a trade-off between the flow allocated and the pollution caused by the uses. The problem can improve using a better estimation for grey WF but generally can show the basin state in the future.

Chapter 6

Conclusions

Climate change impacts on a global scale, producing accelerated temperature increments and climate variability. One of the primary resources affected is water because of the increase in its scarcity and pollution. On the other side, uncontrolled water use produces severe problems for water resources, their quality, and availability, becoming a problem for the population and ecosystems. Therefore, actions must be taken to preserve water resources and decrease water consumption and pollution caused by its use. The focus must be on preserving the resource, caring for the ecosystems, and ensuring access to food and water for everyone. The indicator creation is a starting point to have tools helping to make decisions about water allocation considering social, economic, and environmental aspects and possible consequences.

In this context, the presented work creates a water accounting system and an indicator to assess the basin's water allocation based on the area's availability and needs. The goals were accomplished, and the main results obtained are the following:

1. Creation of a water accounting system based on the basin demand and water pollution caused by the different water uses.
2. Creation of an indicator to assess and define the basin situation and have the necessary information to establish the relations between a basin's environment and social needs. This assessment helps to make decisions in a scarcity context.
3. Using the water tenure concept as a perspective to analyze the indicator results.
4. Application of the indicator in an actual case study, considering the current and future scenario.

First, in Chapter 2, a water accounting system was created to know the water basin utilization, the withdrawals corresponding to each use, and the water pollution related to their process. The system definition is through the water flows abstracted by the uses, and the grey water footprint caused. The accounting system has three components, measure the water abstraction for consumptive uses, the water utilization for non-consumptive uses, and the grey water footprint caused by both uses. Chile's main uses define the accounting system: domestic, agriculture, mining, livestock production, environmental protection, forest industry, hydropower, and aquaculture. Nevertheless, the system is adaptable to the context of any country.

Then, a vectorial indicator was created to assess the basin's current state and help plan future allocation improvements. This creation is essential to basin management in the country because there not are national or regional agreements and regulations helping with the allocation. In contrast, the focus of the indicator is to assess each basin according to its particularities. Then, the indicator can inform public policy decision-makers in water use and management in a basin.

The indicator definition depends on two accounting systems; one measures the basin's current case, and another establishes an ideal scenario. On one side, it compares the needed water amount with the currently used, making the difference between consumptive and non-consumptive uses. Another is the reduction of water pollution regarding a base case. Hence, the indicator is a comparison measure between both systems. As the accounting system, the indicator is a vector of three components. The ideal values are zero for each element because the water used is the same as needed and reaches a total pollution reduction.

Finally, the vectorial indicator was tested in the Tolten River (belonging to the Araucania region). The indicator assessed the current situation in the basin and was utilized in two optimization problems to find an equitable allocation; one, with the current data, and another, in a future scenario considering less water availability and more water demand. Both problems were solved in Julia's language, obtaining the basin water allocation by minimizing the indicator components' weighted sum.

The proposed indicator has a real impact because understanding water management is essential. After all, it defines policies regarding water resources. This work presents the concept of water tenure, which aims to replace water rights because it considers and gives an integrated understanding of the relationship between water and the environment and its needs. Besides, it presents the indicator utility as a tool helping to determine tenure arrangements in a basin when assessing the water use and the pollution associated with the processes of the uses. In this line, the indicator facilitates the water tenure application in a basin because both have similar concepts: the uses hierarchy and the importance of the uses as the base for water allocation, quantification, and regulation. Then the indicator is part of the international discussion about water use and management, and it can be a tool to plan the water systems in the country and the world.

The proposed indicator is adaptable to any country; its methodology allows the assessment of any use set. The kinds of uses can change, but the comparison and calculus will remain the same. If other uses are to be considered, they must include the importance scale for the consumptive component. The level will depend on who is using the indicator and what are the country's social, environmental, and economic necessities.

In the future, the proposed indicator can be improved, for example, by incorporating other aspects to be assessed or having a more accurate ideal scenario definition and current scenario estimation. Through its use, the advantages and aspects to better will be knowing, besides creating new tools or indicators to help and assess water management.

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Annex A

Determination of ideal scenario for agriculture

Determining water requirements for agriculture depends on crop water need, defined as the amount of water necessary to meet the water loss through evapotranspiration [64]. This necessity can be supplied for rainwater, irrigation, or both.

The crop water needs mainly depend on the climate (with higher temperatures, crops need more water per day than with lower temperatures), the crop type, and the growth stage of the crop (fully grown crops need more water than crops that have just been planted) [64].

The climatic factors influencing crop water needs are sunshine, temperature, humidity, and wind speed. Table A.1 explains how each factor affects the crop water need. Hence, the influence of the climate is given by the reference crop evapotranspiration (ET_0), which can be roughly by the values shown in Table A.2 [64].

Table A.1: Effect of the climatic factors on crop water needs

Climatic factor	**Crop water need**	
	High	**Low**
Temperature	hot	cool
Humidity	low/dry	high/humid
Windspeed	windy	little wind
Sunshine	sunny	cloudy

Table A.2: Values of ET_0 $[mm/day]$ by temperature and climate zone's

	Mean daily temperature		
Climatic zone	**Low** ($T < 15$°C)	**Medium** ($T \in [15, 25]$°C)	**High** ($T > 25$°C)
Desert (arid)	4-6	7-8	9-10
Semi arid	4-5	6-7	8-9
Sub-humid (moist)	3-4	5-6	7-8
Humid	1-2	3-4	5-6

In this work, the value of Kc for each crop is an estimation between the values in the beginning (Kc_{beg}), the middle (Kc_{mid}), and the ending (Kc_{end}) of the crop season, in which the mid-season stage is the most important. Equation A.1 shows how it is calculated Kc.

$$Kc = 0.12Kc_{beg} + 0.68Kc_{mid} + 0.2Kc_{end} \tag{A.1}$$

Besides, the actual crop water need depends also on the crop factor, Kc, which is particular for each specie due to depends on its growth stage and the climate factors where it is. The Equation A.4 show the actual crop water needed for one specie (i).

$$ET_{0i} = Kc_i \cdot ET_0 \tag{A.2}$$

On another side, if rainwater is present, it must be considered in the irrigation need calculus. The rainfall does not fully percolate the root zone, so just a part supplies the requirements. When rainwater falls on the soil surface, some of it infiltrates into the soil, some stagnates on the surface, and others over the surface as runoff. Then, when it stops, a part of the water on the surface evaporates into the atmosphere, while the rest slowly infiltrates into the soil. Some percolate below the root zone from all the water that infiltrates the soil, and the rest remains stored in the root zone. Finally, adequate rainfall is the total rainfall minus runoff minus evaporation and minus deep percolation; only the water retained in the root zone can be used by the plants [64].

The Equation A.3 shows how much water is effectively used for the crop (Pe) depending on monthly rainfall (P) [64].

$$Pe = \begin{cases} 0,8P - 25 & \text{if } Pm \geq 75\frac{mm}{month} \\ 0,6P - 10 & \text{if } Pm < 75\frac{mm}{month} \end{cases} \tag{A.3}$$

Finally, the following equation determines the water needs for agriculture:

$$IS_{c,ag} = \frac{\left(\sum\limits_{i \in I} \bar{Kc_i} \cdot ET_0 - Pe\right) A_{ag,i}}{\eta} \tag{A.4}$$

In which I is the set of principal crops in the zone, $A_{ag,i}$ is the i crop area to irrigate, and η is the irrigation system efficiency. To determine the I set, the species regarding 85% of the crop were included.

Annex B

Water tenure

Water tenure is defined as *the relationship, whether legally or customarily defined, between people, as individuals or groups, with respect to water* [21]. Tenure determines how people, communities, and organizations obtain access to and use water resources through the following aspects [21]:

- Who can use it?
- How much can be used and for how long?
- Purpose and under what conditions
- Establish administration to create rights and solution conflicts mechanisms.

So, tenure is recognized as a social construct. Besides, it takes care of claims to specific water resources, understanding it in the environment, and considers the human right to water [21].

There are two types of tenure arrangements, the defined by formal law and the defined by informal law.

B.1. Water tenure arrangements

B.1.1. Defined by formal law

This arrangement refers to the rules created by the country's legislature. The power of the state implemented them and asserted them before the courts. There are ten types of formal arrangements that are following defined [21].

- "Traditional" formal water rights. They derive from land tenure rights. Use water existing in the location. Each landholder values their rights do not exist nor needs an administration.
- "Modern" formal water rights. Created based on a legal instrument. Rights to use and not property. Assigned for a limited time. Water just can be used for the assignment establish.
- Regulatory licenses. They are defined in a short time and are renewable. They regulate different activities that use water resources. They do not constitute any property type.

- Agency control. Facilities a fast development. Give power to hydraulics bureaucracies. They are governmental. The state acts through agencies.
- Water supply contracts. Specials for irrigation (necessity to food security). The users do not have direct access to the resource a service provides to them. How much water is assigned depends on availability. They are annuals.
- Commonhold water tenure. Apply in water Use Organizations (WUO), in general, special for irrigation. All beneficiaries share collective rights. These organizations are autonomous.
- Investment contracts. Investors with the current government, ministry, or governmental agency, use the resources for commercial purposes, so they are conferred rights. It can specify a quantity.
- *De minimis* rights – small scale. Exempt from legal rights or regulatory licenses. They are used for drinking water supply, livelihoods, household needs, livestock, poultry, pets, recreational use, etc.
- Exempt commercial uses. It can be small-scale or commercial. Some places prevent the unrestricted use of water resources on a big scale. Some services don't need formal legal rights or regulatory licenses.
- Reserves/minimum flow requirements. For human consumption and environmental necessities (aquatic ecosystems protection). It considers quality and quantity.

B.1.2. Not Defined by formal law

There are five types of formal arrangements that are following defined [21].

- Customary water tenure. It can regulate access from different societies, tribes, or user groups to have the same resource.
- Religious law. It can be or is not part of customary laws. They depend on and are defined by each religion. For example, the protection of important religious areas.
- Informal water tenure. This type is not recognized legally. Usually are tolerated for convenience o because the law is poorly adapted.
- Assumed rights and impossible rights. Assumed appear when governments or state agencies build infrastructure for supply or irrigation purposes. Impossible appears when an entity can not possess a legal water right. For example, small-scale supplies like villages or settlements.
- Unrecognized water tenure. This type does not involve abstraction and/or impoundment of water but has invisible effects, as in the quality.

B.2. Water tenure uses

There are categories of use in tenure, which depend on the water objective. These categories are related to tenure arrangements. Each category, and its usual arrangements type, is described at following [21].

- Domestic. It refers to supply for municipal users and uses. The types of arrangements are traditional formal water rights and modern formal water rights.
- Agriculture. It refers to stock water purposes and, in particular, irrigation. Almost every type of water tenure arrangement apply to them.
- Industry. It refers to larger industrial operations, factories, and large plants. Industrial countries use supply contracts or modern formal water rights. Developing countries use supply contracts or informal water tenure.
- Hydropower. Turbines use water to generate electricity. The types of arrangements are modern formal water rights (for countries that implement them), control agencies (state actors), or investment contracts (developing countries).
- Environment. Water flow is used to maintain and supply the ecosystem's necessities. The types of arrangements are reserves/minimum flow requirements, traditional formal water rights acquire by the non-governmental organization, trust, or state.
- Navigation. Water legislation usually seeks to protect navigation interests. Distinguish between a navigable course of water and not. The types of arrangements are *minimis* rights reserved to navigation and regulatory license to inland navigation.
- Inland fisheries and other non-consumptive livelihood activities. Does not recognize by formal law. They can be protected by customary water tenure. In aquaculture, the types of arrangements are supply contracts or modern formal water rights. The fishery can be recognized as a potential water user organization.
- Recreation, landscape, and tourism. Reserves/minimum flow requirements or *minimis* rights for this use.

B.3. Advantages and disadvantages of water tenure

Table B.1 summarize the advantages and disadvantages of water tenure [21].

Table B.1: Argurments of water tenure.

Arguments in favour	**Arguments against**
Holistic: shows things as they are	Does not exist a need for a new concept
Non-prescriptive	Complex and theoretical
More sensitive and nuanced approach	Only of interest to lawyers
Policy coherence and the land-water linkage	Always has used the term "water rights"
Multidisciplinary	
Focus on users	

Annex C

Study case: Rio Tolten basin

C.1. Flow

The flow per month determination of the basin is obtained from the tool *CAMELS-CL explorer* [78][10]. The basin comprises thirteen sub-basin; for the analysis, it considered the data between 2015 and 2018 because they are the last four years with complete data. It is considered the annual mean flow for each year. Table C.1 shows the flow registered in $[m^3/s]$

Table C.1: Annual average water flow in the Tolten river basin between 2015 and 2018

Year	**Average flow** $[m^3/s]$
2015	578.8
2016	351.0
2017	504.2
2018	531.5

The calculus for the average flow in the Tolten river basin is 491.4 $[m^3/s]$, equivalent to 15.495.765 $[km^3/y]$.

C.2. Population to supply

The determination of the population to supply the basin is obtained from *Censo 2017* data. The population is considered the same as this analysis and belongs to Melipeuco, Cunco, Freire, Teodoro Schmidt, Curarrehue, Pucón, Pitrufquén, Toltén, Gorbea, Villarrica, and Loncoche communes [79]. Being the total population to supply the sum of each one. The data is shown in Table C.2.

---

[10] Download basin data of *9437002 - Rio Tolten En Teodoro Schmidt*

Table C.2: Population of communes supplied by Rio Tolten basin [82]

Commune	**Population**
Cunco	17,526
Curarrehue	7,489
Freire	24,606
Gorbea	14,414
Loncoche	23,612
Melipuco	6,138
Pitrufquén	24,837
Pucón	28,523
Teodoro Schmidt	15,045
Toltén	9,722
Villarica	55,478

C.3. Determination of Tolten river basin percentage demand

According to the DGA database, in the Araucania region, there are 20,490 rights awarded equal to $2.58{\cdot}10^{13}\ m^3/y$, of which $8.40{\cdot}10^{12}\ m^3/y$ belong to Tolten river basin [109][11]. From these data, it has to obtain that 32.5% of the flow is allocated in the basin.

It uses this ratio to estimate the water footprint and ideal case for uses without information.

C.4. Agriculture flow determination

In this work, the value of Kc for each crop is an estimation between the values in the beginning (Kc_{beg}), the middle (Kc_{mid}), and the ending (Kc_{end}) of the crop season, in which the mid-season stage is the most important. The values for each species are shown in Table C.3, and Equation C.1 shows how it is calculated Kc.

---

[11] Download document *IX Región de la Araucanía* in *Listado de derechos concedidos por región.*

Table C.3: Crop coefficients in different stages

Crop	Kc_{beg}	Kc_{mid}	Kc_{end}
Wheat	0.3	1.1	0.325
Oatmeal	0.3	1.1	0.25
Rape	0.35	1.025	0.35
Triticale	0.5	1.16	0.25
Potato	0.5	1.1	0.75
Lupine	0.4	1.15	0.35

$$Kc = 0.12Kc_{beg} + 0.68Kc_{mid} + 0.2Kc_{end} \tag{C.1}$$

C.5. Mining industry

The Chilean mining industry stands out for copper mining, which is fundamental in the national economy [72]. Just copper mining use 87.4% of water use in mining [110], and its production for 2020 was 5,730,000 t. Although copper is the main mineral, iron has the highest production, reaching 9,890,000 t in 2020. For the Chilean case, the analysis and estimation of water consumption is only for copper and iron.

To join all these uses for the calculus of water consumption, it utilizes a factor representing how much water needs all mining processes regarding the mineral mass that must be treated. Research determines, based on different mining industries that the water flow for copper production is 69.21 m^3 for mineral ton, and the water flow for iron production is 0.598 m^3 for mineral ton.

The general equation for the ideal case of the mining industry is the following:

$$IS_{c,min} = \sum_{i \in I} f_i \cdot MM_i \tag{C.2}$$

in which f_i is the consumption rate for mineral i, MM_i is its mass to process per month, and I is the set of minerals produced by the country.

Table C.4: Water consumption rate for mining operations

	$f\ [m^3/ton - min]$
Concentration	0,99
Hydrometallurgy	0,28
Others	0,1

C.6. Future scenario

Researchers expect a decrease in the monthly streamflows for 2040–2070. The worst case will be in summer, with a decrease of 19% ± 6%, and the better case in autumn, with 18% ± 9% [107]. So, for this study, the basin flow available ($q_{f,avail}$) will be the current flow (q_{avail}) reduced by 25%, which corresponds to the summer worst scenario. The calculus is shown in Equation C.3.

$$\begin{aligned} q_{f,avail} &= 0.25 q_{avail} \\ &= 0.25 \cdot 15.495.765 \left[\frac{km^3}{y} \right] \\ &= 10.434.688 \left[\frac{km^3}{y} \right] \end{aligned} \tag{C.3}$$

The total water demand will increase over the years, and it can even double by 2050 [108]. The new demand or water requirement (i.e., ideal case) for each use, except environmental protection, is double than current. Although it considers a reduction in the basin streamflow, the flow for environmental protection will not change because the water requirement is not proportional to the volume depending on the basin ecosystems. The new ideal values (qid_{fs}) are determined based on the current scenario (qid) as following show.

- Domestic:

$$\begin{aligned} qid_{fs,dom} &= 2 qid_{dom} \\ &= 29,049 \left[\frac{km^3}{y} \right] \end{aligned} \tag{C.4}$$

- Agriculture:

$$\begin{aligned} qid_{fs,ag} &= 2 qid_{ag} \\ &= 29,294 \left[\frac{km^3}{y} \right] \end{aligned} \tag{C.5}$$

- Mining:

$$qid_{fs,min} = 0 \tag{C.6}$$

- Livestock production:

$$\begin{aligned} qid_{fs,lp} &= 2 qid_{lp} \\ &= 6,600 \left[\frac{km^3}{y} \right] \end{aligned} \tag{C.7}$$

- Environmental protection:

$$\begin{aligned} qid_{fs,ep} &= qid_{ep} \\ &= 3,311,280\left[\frac{km^3}{y}\right] \end{aligned} \tag{C.8}$$

- Forest industry:

$$\begin{aligned} qid_{fs,for} &= 2qid_{for} \\ &= 7,042,242\left[\frac{km^3}{y}\right] \end{aligned} \tag{C.9}$$

- Hydropower:

$$\begin{aligned} qid_{fs,hp} &= 2qid_{hp} \\ &= 1,752,903\left[\frac{km^3}{y}\right] \end{aligned} \tag{C.10}$$

- Aquaculture:

$$\begin{aligned} qid_{fs,aq} &= 2qid_{aq} \\ &= 343,233\left[\frac{km^3}{y}\right] \end{aligned} \tag{C.11}$$

Annex D

Code

Code D.1: Current scenario optimization

```
#Author: Francisca Javiera Andonie Bahamondes, University of Chile
#The implemented code developed within the scope of the master thesis, "A water allocation
    ↪  indicator for hydrographic basins"

#Model generation
import Pkg
using Pkg
Pkg.add("Ipopt");

using JuMP, Ipopt, DataFrames

w_alloc = Model(Ipopt.Optimizer)
set_optimizer_attribute(w_alloc, "max_cpu_time", 300.0)
set_optimizer_attribute(w_alloc, "print_level", 3)
set_optimizer_attribute(w_alloc, "tol", 0.00000005)


#Sets definition
C = ["dom", "ag", "min", "lp", "ep"] #consumptive uses
NC = ["for", "hp", "aq"] #non-consumptive uses
U = vcat(C, NC) #all uses
Crop = ["wheat", "oatmeal", "rape", "triticale", "potato", "lupine"] #Crops type
An = ["beef_cattle", "sheep", "swine"] #Animals
I = [1, 2, 3] #indicators
#Sets size
lenC = length(C)
lenNC = length(NC)
lenU = length(U)

#Uses
UDict = Dict{Float64, String}() #Kc
UDict[1] = "dom"
UDict[2] = "ag"
UDict[3] = "min"
UDict[4] = "lp"
UDict[5] = "ep"
UDict[6] = "for"
```

```
UDict[7] = "hp"
UDict[8] = "aq"

#Parameters definition
perc = 0.325 #Percentage of Tolten river basin in Araucania region
%qmax = 109.78 #Max withdrawal flow km3/y
qavail = 15495765.480 #Flow available km3/y

#domestic
qidp = 0.063875 #Ideal flow per person km3/y
Pop = 227390 #Ideal population to supply
qd_id = qidp*Pop

#agriculture
ef = 0.75 #Irrigation efficiency
Pe = 1070.79316666667 #mm/y
ETo = 1277.5 #Evapotranspiration mm/y
Kc = Dict{String, Float64}() #Kc for main crops
Kc["wheat"] = 0.8490
Kc["oatmeal"] = 0.8340
Kc["rape"] = 0.8090
Kc["triticale"] = 0.8988
Kc["potato"] = 0.9580
Kc["lupine"] = 0.9
sf = Dict{String, Float64}() #Surface by crop m2
sf["wheat"] = 911401848.9841430
sf["oatmeal"] = 802671468.9876410
sf["rape"] = 260482826.2118190
sf["triticale"] = 147858108.1376620
sf["potato"] = 111161460.8674640
sf["lupine"] = 85790654.8112705
qag_id = (perc/ef)*sum((Kc[c]*ETo-Pe)*sf[c]/1000000 for c in Crop) #Ideal agriculture water demand km3/y

#mining no parameters
qm_id = 0 #Ideal mining water demand km3/y

#livestock production
wrL = Dict{String, Float64}() #Water requirements per animal L/d
wrL["beef_cattle"] = 51.5
wrL["sheep"] = 2.24
wrL["swine"] = 15
nAn = Dict{String, Float64}() #Number of animals
nAn["beef_cattle"] = 479438
nAn["sheep"] = 208646
nAn["swine"] = 177451
qlp_id = perc*sum(wrL[a]*nAn[a]*365/1000000 for a in An) #Ideal livestock production water demand km3/y

#environmental protection
#Ab = 84460000 #Basin area m2
#PETo = 1030.35975 #Potential evapotranspiration basin mm/y
```

```
qec = 105 #Ecologic flow m3/s
qep_id = qec*3600*24*365/1000 #Ideal environmental protection water demand km3/y

#forest industry
Pp = 1713.49145833333 #Annual precipitation mm/y
Afor = 6322890000 #Forest area m2
qf_id = perc*Afor*Pp/1000000 #Ideal forest industry water requirement km3/y

#hydropower
qhp_id = 876451.6656 #Ideal hydropower water requirement km3/y

#aquaculture
mSal = 418609.202537905 #Salmon mass kg
wrSal = 1.26144 #Water requirements per salmon kg Mm3/kg-y
qaq_id = perc*wrSal*mSal #Ideal aquaculture water requierement km3/y

qid = Dict{String, Float64}() #Ideal flow km3/y
qid["dom"] = qd_id
qid["ag"] = qag_id
qid["min"] = qm_id
qid["lp"] = qlp_id
qid["ep"] = qep_id
qid["for"] = qf_id
qid["hp"] = qhp_id
qid["aq"] = qaq_id

#grey WF
gWFb = Dict{String, Float64}() #Basis grey WF
gWFb["dom"] = 187633.30406471
gWFb["ag"] = 457473.713093037
gWFb["min"] = 0
gWFb["lp"] = 0.995301474802201
gWFb["ep"] = 0
gWFb["for"] = 30141.1224562793
gWFb["hp"] = 0
gWFb["aq"] = 75.124920521369
fg = Dict{String, Float64}() #Pollution rate
fg["dom"] = 6.54598849290596
fg["ag"] = 7.63796483961393
fg["min"] = 0
fg["lp"] = 0.000147669601734883
fg["ep"] = 0
fg["for"] = 0.00260890724043116
fg["hp"] = 0
fg["aq"] = 0.000000878145498694946


#Conditions and variables
@variable(w_alloc, q[u in U] >= 0) #Water flow per use Mm3/y
@variable(w_alloc, gWF[u in U] >= 0) #grey WF per use Mm3/y
@variable(w_alloc, delta1[c in C]) #ratio for indicator 1, (r-id)/id
@variable(w_alloc, N1i >= 0) #difference for indicator 1, 1-r
```

```
@variable(w_alloc, delta2[nc in NC]) #delta for indicator 2
@variable(w_alloc, N2j >= 0) #difference for indicator 2
@variable(w_alloc, delta3[u in U]) #delta for indicator 3
@variable(w_alloc, N3k >= 0) #difference for indicator 3
@variable(w_alloc, Ind[i in I]) #Indicators value

JuMP.fix(q["min"], 0, force= true) #fix the value of mining flow

#Constraints
#Do not use more than basin capacity
@constraint(w_alloc, sum(q[au] for au in U) <= qavail)
#Fullfiment demand
for u in U
    @constraint(w_alloc, q[u] - qid[u] >= 0)
end
#Pollution per use
for u in U
    @constraint(w_alloc, fg[u]*q[u] == gWF[u])
end

#Indicators
#Difference indicator 1
for c in C
    if c == "min"
        @constraint(w_alloc, delta1[c] == 0)
    else
        @constraint(w_alloc, delta1[c] == (q[c] - qid[c])/qid[c])
    end
end
#N1i
@NLconstraint(w_alloc, N1i == sum((0 - delta1[c])^2 for c in C)/(lenC - 1))
#Indicator 1
@NLconstraint(w_alloc, Ind[1] == sqrt(N1i))

#Percentage difference indicator 2
for nc in NC
     @constraint(w_alloc, delta2[nc] == (q[nc] - qid[nc])/qid[nc])
end
#Almost definition ind 2
@NLconstraint(w_alloc, N2j == sum((0 - delta2[nc])^2 for nc in NC)/lenNC)
#Indicator 2
@NLconstraint(w_alloc, Ind[2] == sqrt(N2j))

#Difference indicator 3
for u in U
    if gWFb[u] == 0
        @constraint(w_alloc, delta3[u] ==  0)
    else
        @constraint(w_alloc, delta3[u] ==  1 - (gWFb[u] - gWF[u])/gWFb[u])
    end
end
#Almost definition ind 3
```

```
@NLconstraint(w_alloc, N3k == sum((0 - delta3[u])^2 for u in U)/(lenU-3))
#Indicator 3
@NLconstraint(w_alloc, Ind[3] == sqrt(N3k))

#Objective function
@objective(w_alloc, Min, 2*Ind[1] + Ind[2] + 0.5*Ind[3])
optimize!(w_alloc)
getobjectivevalue(w_alloc)


#Results
#Uses
Uv = [k for k=1:lenU]
df_results = DataFrame(Use = [], IdealValue = [], RealValue = [], GreyWF = [])
for k in Uv
    Use = UDict[k]
    IdealValue = qid[UDict[k]]
    RealValue = value.(q[UDict[k]])
    GreyWF = value.(gWF[UDict[k]])
    push!(df_results,hcat(Use, IdealValue, RealValue, GreyWF))
end
println("Results")
show(df_results)

df_indicator = DataFrame(indicator = [], number = [], Value = [])
for i in I
    indicator = "Indicator"
    number = i
    Value = value.(Ind[i])
    push!(df_indicator,hcat(indicator, number, Value))
end
println(" ")
println(" ")
println("Vectorial indicator results")
show(df_indicador, allrows=true, allcols=true)
```

For the future scenario, the model is the same but with the change in available basin flow, uses ideal flows, and demand constraints, as it is shown in the following part of the code:

Code D.2:

```
qavail = 10434668.0027706 #new available flow km3/y

qid = Dict{String, Float64}() #new ideal flow km3/y
qid["dom"] = 2*qd_id
qid["ag"] = 2*qag_id
qid["min"] = 2*qm_id
qid["lp"] = 2*qlp_id
qid["ep"] = qep_id
qid["for"] = 2*qf_id
qid["hp"] = 2*qhp_id
```

```
qid["aq"] = 2*qaq_id

#changes in constraints
#Pollution per use
for u in U
    @constraint(w_alloc, fg[u]*q[u] == gWF[u])
end
```