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Risk and sustainability assessment (RSA) framework for 'water scarcity – water reuse' situations

Conceptualisation, operationalisation, and testing

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Dresden, 16 January 2023

Müller, Andrea Beatrix

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Abstract

The number of regions undergoing water scarcity, where the quantity of available water is not enough to meet human demand, is expected to increase in the future. Water reuse measures have been widely implemented to face these situations as a means of increasing the supply of water resources. Thus, 'water scarcity – water reuse' (WS-WR) situations will likely become more common. In these cases, water resources management to secure enough water supply is key. Risk and sustainability concepts have been consolidated as guiding discourses that also support the management of water resources. In particular, in the case of WS-WR situations, they can guide decision-makers towards reducing the risk of water scarcity and striving for the implementation of sustainable water reuse measures. In particular, the use of risk and sustainability assessments helps to deal with various social, economic, and environmental requirements and constraints. However, there is still the call for a more comprehensive and integrated assessments.

This dissertation aims at providing new ideas for the integration of risk and sustainability in the case of WS-WR situations. Three objectives guide this research: (A) to develop a conceptual assessment framework to support decision-making concerning sustainable water reuse in regions facing risk of water scarcity; (B) to advance the conceptual framework interrelating existing risk and sustainability assessment methodologies and indicators in the context of decision support; and (C) to test the conceptual and methodological framework using a case study in Latin America. Each objective is associated with a research question: (RQ1) How is decision-making regarding water reuse understood and supported towards reducing the risk of water scarcity sustainably – and how can it be represented in a conceptual assessment framework?; (RQ2) How can a conceptual framework for assessing water reuse as sustainable water scarcity risk reduction measures be operationalised through a methodological framework?; and (RQ3) What are the findings from testing the framework in a case study – and what can be incorporated into the framework? Each objective and its respective research question was addressed as a separate step of the research approach, comprising the development of an integrated Risk and Sustainability Assessment (RSA) Framework for WS-WR situations, its operationalisation and testing. The research approach followed a deductive to inductive rationale relying on qualitative and quantitative methods. The outputs of this research are three scientific publications that build this cumulative dissertation (two published and one submitted for revision).

The development of the conceptual framework followed three steps: (i) defining the concepts of 'water scarcity', 'water reuse', 'risk' and 'risk assessment', 'sustainability' and 'sustainability assessment', and 'decision-making'; (ii) integrating these concepts by interpreting water scarcity from a risk perspective and water reuse from a sustainability perspective, and relating assessments with decision-making; and (iii) structuring the RSA Framework, following a risk assessment and framing it by the social, economic, and environmental dimensions of sustainability. Results allowed defining decision-making in WS-WR situations as a four-step cyclic process that can be supported by an integrated RSA that comprises an analysis (descriptive and objective) and evaluation (subjective).

The methodological aspects for the operationalisation of the RSA conceptual framework focused mainly on developing an analytical concept to support an adequate derivation of the information required in an integrated RSA for WS-WR situations. The resulting concept is based on (i)

understanding the WS-WR situation as a Coupled Human and Natural System (CHANS) and identifying the main biophysical elements (*endpoints*); (ii) translating the CHANS *endpoints* into an information system via a Multi-Layer (ML) approach using generic *descriptors* and specific *indicators*; and (iii) identifying and characterising interlinkages between the *indicators* via a Lane-Based (LB) approach. Additional methodological aspects related to the evaluation include the use of indicator-based multi-criteria decision-making methods that include the weighting and aggregation of these indicators, as well as the selection of threshold values as evaluation criteria.

The testing of the integrated RSA Framework was carried out in Cerrillos de Tamaya, Chile. It involved an *ex-post* RSA of a water reuse measure implemented in 2018 to face the local water scarcity situation. The testing included (i) describing the case study location and adapting the RSA Framework to fit the local context; (ii) translating the case study's CHANS via the ML approach and identifying and characterising interlinkages via the LB approach; and (iii) evaluating the degree of risk of water scarcity and sustainability of water reuse via the distance-based method TOPSIS. The results of the testing provided feedback for the RSA Framework. These mainly referred to the influence of the conceptualisation behind the indicators and their use, and the methodological challenges for integrating risk and sustainability evaluation. Further recommendations to the RSA framework are: the inclusion of interlinkage directionality; the use of existing system dynamics modelling approaches (e.g., CLD, SFD); the development of an established database of indicators; the automation of the interlinkages analysis (LB approach); and advance the use of scenarios for sustainability evaluation for better coupling with risk evaluation methods.

Overall this research provides evidence of (a) the conceptual integration of risk and sustainability discourses under one decision support framework for the case of WS-WR situations; (b) the use of a system thinking approach for interpreting the WS-WR situation; (c) the relevance of indicators as a means of representing the situation; (d) the interlinkage of social, economic, environmental information; (e) the benefits of the use of conceptual maps; (f) gaps in the process of measuring the effect of water reuse on water scarcity levels via indicators; (g) the gap between a simulation-based risk assessment and a snapshot-focused sustainability assessment that hinders an operational integration; (h) the possibility of the RSA framework to bridge a system thinking view with a traditional assessment-based decision-making view.

Contents

Acknowledgements ..... **v**

Abstract ..... **vii**

Contents ..... **ix**

List of Figures ..... **xi**

List of Tables ..... **xii**

Acronyms and Abbreviations ..... **xiii**

Symbols ..... **xiv**

Chapter 1 - Introduction **1**

1.1 Background and problem statement 1
1.1.1 Water resources for water security 1
1.1.2 Risk and sustainability discourses for water-related decision-making 3
1.1.3 Problem statement and research focus 8
1.2 Objectives and research questions 10
1.3 Research approach and structure of the document 10
1.3.1 Research approach 10
1.3.2 Structure of the document 13
1.4 Chapter references 15

Chapter 2 - Conceptual Framework **19**

2.1 Introduction 20
2.2 Developing the conceptual framework 22
2.2.1 Definition and interpretation of the subject at stake 23
2.2.2 Identification and definition of key concepts 25
2.2.3 Construction of the conceptual framework 25
2.3 Results and discussion 26
2.3.1 Defining and interpreting the 'water scarcity – water reuse' situation 26
2.3.2 Identifying and defining key concepts 29
2.3.3 Construction of the integrated RSA Framework 35
2.4 Conclusions and outlook 42
2.5 Acknowledgements 43
2.6 Chapter references 43

Chapter 3 - Methodological Aspects **51**

3.1 Introduction 52
3.2 RSA Framework for a WS-WR situation 53
3.3 Systems thinking in a WS-WR situation 54
3.3.1 Identifying elements of a WS-WR situation and its interpretation as a system 54
3.3.2 Translation of the CHANS into an information system 55
3.4 Characterisation and interlinkage of indicators 57
3.4.1 Type and number of indicators 58
3.4.2 Type and number of interlinkages 58
3.4.3 Indicator connectivity 59
3.4.4 Structuring via a lane-based approach 59
3.5 RSA analytical concept and exemplification 60
3.5.1 RSA analytical concept 60

3.5.2 Exemplification of the analyitical concept 61
3.6 Discussion 68
3.6.1 Translating the CHANS into an information system 68
3.6.2 Supporting decision-making via the analytical concept 69
3.7 Conclusions 71
3.8 Acknowledgements 72
3.9 Chapter references 72

Chapter 4 - Framework Testing 77
4.1 Introduction 78
4.2 Approach 78
4.2.1 RSA Framework 78
4.2.2 Case study site 84
4.3 Results 87
4.3.1 Analysis 87
4.3.2 Evaluation 94
4.3.3 General results for the case 96
4.4 Discussion 99
4.4.1 Analysis 99
4.4.2 Evaluation 101
4.4.3 Overall discussion on the testing of the RSA Framework 103
4.5 Conclusions 104
4.6 Acknowledgements 105
4.7 Chapter References 105

Chapter 5 - Synthesis 109
5.1 Conceptual aspects 109
5.2 Methodological aspects 111
5.3 Testing aspects 113
5.4 Placing the RSA Framework in a broader context 114
5.5 Chapter References 116

Chapter 6 - Conclusions and Outlook 119

Annexes 123
Annex A - Literature review: Found records 125
Annex B - Example list of endpoints, descriptors, indicators, and attributes 127
Annex C - Technique for Order Preference by Similarly to Ideal Solution (TOPSIS) 133
Annex D - Translation into the Information System (from endpoints to attributes) 143
Annex E - Interlinkages Identification Matrix 151
Annex F - List of Most Interlinked Indicators (MII) 159
Annex G - List of indicators, scores, and thresholds 162

List of Figures

Figure 1.1: List of the seven global targets set in the Sendai Framework 2015–2030 ... 4

Figure 1.2: Icons of the 2030 Agenda 17 Sustainable Development Goals (SDGs) ... 5

Figure 1.3 Risk and sustainability milestones of the past 40 years ... 6

Figure 1.4: Schematic view of the focus of this research within water resources management ... 9

Figure 1.5: Objectives and research questions (RQs) ... 10

Figure 1.6: Research approach according to the objectives ... 11

Figure 1.7: Proportion of household wastewater safely treated in Latin America.. ... 12

Figure 1.8: Schematic representation of the chapters of this document, their content and alignment with the research objectives and approach. ... 14

Figure 2.1: Graphical abstract ... 20

Figure 2.2: Schematic view of the approach and obtained results for the development of the integrated RSA Framework. ... 23

Figure 2.3: Presentation of a 'water scarcity – water reuse' situation considering either (a) independent decision-making or (b) the proposed integrated approach. ... 24

Figure 2.4: Tackling the 'water scarcity – water reuse' situation as a coupled human and natural system. ... 25

Figure 2.5: Representation of the 'water scarcity – water reuse' situation as a simplified CHANS. 28

Figure 2.6: Decision-making as the sequence of steps to make a choice considering data and information. ... 34

Figure 2.7: Water scarcity and water scarcity as a risk presented as functions. ... 35

Figure 2.8: Integrated Risk and Sustainability Assessment (RSA) Framework. ... 39

Figure 3.1: Integrated RSA comprising analysis and evaluation ... 54

Figure 3.2: Representation of the ML approach ... 56

Figure 3.3: Lane-based approach for visualising the WS-WR information system. ... 60

Figure 3.4: Analytical concept embedded in the RSA Framework. ... 61

Figure 3.5: Overview of the lane-based visualisation of all layers ... 65

Figure 4.1 Main components of the integrated RSA Framework ... 79

Figure 4.2 Weighting and aggregation scheme. ... 84

Figure 4.3 Study site in the Coquimbo Region. ... 86

Figure 4.4 System for the case of Cerrillos de Tamaya. Modified from Müller et al. (2020) ... 88

Figure 4.5 Evaluation results ... 96

Figure 4.6 Overview of the lane-based visualisation of all layers. ... 97

Figure 5.1: Integrated RSA ... 115

List of Tables

Table 1.1: Dimensions to report the degree of implementation of IWRM 7

Table 2.1: Selected water scarcity and water stress definitions 30

Table 2.2: Definitions of water scarcity and water stress applied for the integrated RSA Framework 31

Table 2.3: Working definitions for water reuse and reclamation 32

Table 2.4: Definitions on risk for the integrated RSA Framework 32

Table 2.5: Definitions on sustainability for the integrated RSA Framework 33

Table 2.6: Water scarcity as a risk: definition in terms of the risk dimensions 36

Table 2.7: Water reuse as a sustainable measure 37

Table 3.1: Information that can be derived from the information system 57

Table 3.2: Information about type and number of interlinkages 58

Table 3.3: Literature review search string and results 62

Table 3.4: Selected example endpoints, descriptors, indicators, and attributes 63

Table 3.5: Data of the example system 64

Table 4.1 Number of indicators and interlinkages considered for the analysis. 90

Table 4.2 Multi-layer approach in a tabular layout 92

Table 4.3 Examples of the interlinkage identification matrix 93

Table 4.4 Summary of the number of indicators used and not used in the evaluation. 94

Acronyms and Abbreviations

Item	Meaning
AHP	Analytical Hierarchy Process
BOD	Biochemical Oxygen Demand
BPMN	Business Process Model and Notation
CAF	Development Bank of Latin America
CHANS	Coupled Human and Natural System
Ec.	Economic
En.	Environmental
HDI	Human Development Index
HES	Human-Environment System
IDNDR	International Decade for Natural Disaster Reduction
il.	Interlinkage
IWRM	Integrated Water Resources Management
LB	Lane-Based
MCDM	Multi-Criteria Decision-Making
MDG	Millennium Development Goal
ML	Multi-Layer
R	Risk
RA	Risk Assessment
RSA	Risk and Sustainability Assessment
S	Sustainability
SA	Sustainability Assessment
SDG	Sustainable Development Goal
SES	Social-Ecological System
So.	Social
SPI	Standardised Precipitation Index
SSI	Standardised Streamflow Index
SSP	Shared Socioeconomic Pathway
TBL	Triple Bottom Line
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
TWW	Treated Wastewater
UN	United Nations
UN-Habitat	United Nations Human Settlements Programme
UNDESA	United Nations Department of Economic and Social Affairs
UNDRO	United Nations Disaster Relief Office
UNDRR	United Nations Office for Disaster Risk Reduction
UNEP	United Nations Environment Programme
UNISDR	United Nations International Strategy for Disaster Reduction
WEF	Water–Energy–Food
WR	Water Reuse
WS	Water Scarcity
WS-WR	Water Scarcity – Water Reuse
WSI	Water Stress Index
WW	Wastewater
WWTP	Wastewater Treatment Plant

Symbols

Symbol	Meaning
A^*	Positive-ideal solution
A^-	Negative-ideal solution
B	Benefit indicators
C	Cost indicators
D	TOPIS subdomain scores
d_j	Minimum feasible value of D_j
$P_i{}^*$	Relative closeness of the ith alternative to the positive-ideal solution
r_{ij}	Normalised indicator data value for the ith alternative and jth indicator
$S_i{}^*$	Distance of the ith alternative to the positive-ideal solution
$S_i{}^-$	Distance to the negative-ideal solution
v_{ij}	Weighted normalised value
$v_j{}^*$	Best possible value for indicator j
$v_j{}^-$	Worst possible value for indicator j
w_j	Weight of the jth indicator
x_{ij}	Non-normalised indicator data value

Risk and sustainability assessment (RSA) framework for ‘water scarcity – water reuse’ situations

Conceptualisation, operationalisation, and testing

Chapter 1 Introduction

1.1 Background and problem statement

1.1.1 Water resources for water security

Water is a fundamental resource for life and consequently indispensable for all human activities. Thus, it has not only ecological importance but also a social and economic value that allows establishing a directly proportional relationship between population growth and water demand (when the population grows, so does the water demand) (Hanemann 2005; Kumar et al. 2018). This relationship is based on the water withdrawals necessary to meet the growing water demand of human activities – broadly categorised as agricultural, industrial, and municipal (domestic) uses (FAO n.d.). Thus, management that secures an adequate supply of water resources is critical for sustainable development (Mukate et al. 2017).

Water security is a widely used term that has gained relevance over the past years, although a unique strict definition is difficult, varying between different disciplines and sectors (Gain et al. 2016). UN-Water (2013, 1) proposed defining water security as "*the capacity of a population to safeguard sustainable access to adequate quantities of acceptable quality water for sustaining livelihoods, human well-being, and socio-economic development, for ensuring protection against water-borne pollution and water-related disasters, and for preserving ecosystems in a climate of peace and political stability*". Therefore, it ultimately refers to water management concerning the quantity, quality, and accessibility. Additionally, the World Risk Report (Mucke et al. 2019) highlights a subtle but relevant difference between two perspectives of water security, that of water security *from* water and water security *through* water. *From* water refers to the protection against water-related disasters that hinder an adequate supply of water resources (e.g., floods, droughts, water-related conflicts), and *through* water to the provision of water for safe human consumption. To operationalise the water security concept – considering both perspectives – Gain et al. (2016) propose four primary points: (1) availability of sufficient water resources quantity; (2) accessibility and affordability of water resources; (3) quality and risk characteristics (e.g., contamination, floods); and (4) governance and management aspects. This operationalisation again focuses on the core aspects of quantity, quality, and accessibility, while including the respective management to ensure an adequate supply and protection from/through water resources.

Certainly, challenges to water security can affect all the aspects mentioned above. The first question to ask is whether there is enough water, as sufficient quantities of water resources are not always available where and when needed. Water resources are distributed differently across space and time, given geographic and seasonal conditions. For instance, South America holds around 30% of the global freshwater indicating a rather rich region where water quantity should not be an issue (Sempris 2012; FAO 2017; Bezerra et al. 2021). However, this region includes not only a great extension of rainforest but also one of the driest areas in the world, evidencing the contrasting spatial distribution of water resources. Management strategies and decision-makers need to recognise such crucial factors to secure an adequate supply and protection of water resources.

One of the water quantity issues is the imbalance between the supply and demand of water resources in which the supply is not able to fulfil the demand, also understood as water scarcity (more definitions of this concept in Chapter 2). Global projections indicate that water scarcity issues are expected to increase in the coming years (Veldkamp et al. 2016). Drivers of such situations are both climatological and anthropological (ibid.). Climate-related factors (especially precipitation and temperature) influence a decrease in water quantities, i.e., a decrease in the supply of water resources (UNDRR 2021). Consequently, drought event trends indicate an increase in frequency and severity for Southern Europe, West Africa, Central and South America, Central Asia, and Southern Australia (ibid.). Anthropological drivers mainly refer to population growth, increasing the demand of water reosurces; the population is projected to reach between 8.5 and 10 billion by 2050, depending on the Shared Socioeconomic Pathway (SSP) scenario (KC and Lutz 2017; UNDESA 2019), inherently translating into an increase in water demand. In isolation, a decrease in supply and increase in demand can drive water scarcity, but a simultaneous occurrence of these supply and demand affections can aggravate a water scarcity situation. Different interplays of both drivers in time and space result in projections indicating that by 2050 more than half of the population will live in water-scarce areas, representing an increase of more than 120% since 2016 (He et al. 2021). Thus, the risk of facing water scarcity will considerably increase in the future.

Management strategies to face such situations are various and focus on addressing either or both the supply (e.g., water reuse, desalination; e.g., Chhipi-Shrestha et al. 2017; Ricart and Rico 2019) and the demand (e.g., awareness-raising campaigns, investing in water-saving technologies; e.g., Tang et al. 2013; He et al. 2021) of water resources. For the supply of water resources, water reuse measures – understood as the use of treated wastewater (more details in Chapter 2) – have been widely implemented, especially in cases of water scarcity (e.g., Upadhyaya and Moore 2012; Garcia and Pargament 2015; Fito and Van Hulle 2020). These experiences and technological advances have set the basis for an increase in the implementation of water reuse, as countries have already included such measures in their water resources management plans and regulations (WWAP 2017). For instance, the European Union Parliament has recently published a regulation on the minimum requirements for water reuse (European Parliament 2020). These measures aim at an overall efficient use of water resources that aligns with a circular economy thinking and thus have been flagged as sustainable (e.g., Wilcox et al. 2016; El Moussaoui et al. 2017). However, its successful implementation is not straightforward and involves both conceptual and practical factors. First, efficiency and circularity do not necessarily mean increased sustainability, nor do they imply a decrease in the use of water resources (Avellán et al. 2022). For instance, the idea of circularity provided by water reuse rather than implying a release in the pressure on freshwater resources could offer the illusion of endless water resources (e.g., Bell 2015) that could increase water demand. This has been already reported in the case of basin transfer measures to increase supply (e.g., Madani and Mariño 2009). Such a view focused on the water reuse solution only rather than on the initial situation that motivated its implementation, e.g., water scarcity, leads to a loss of the long-termed intention of water security, replacing it by a short-sighted view. Second, there are additional institutional, social, and economic barriers for the implementation of water reuse, from subjective aspects such as perception and acceptance to strong financial arrangements (e.g., to support the needed technology) (Mainali et al. 2011; Rice et al. 2016; Sgroi et al. 2018). That being so, the variety of factors that decision-makers need to consider for a sustainable implementation of water reuse calls for more comprehensive decision support frameworks (Sgroi et al. 2018).

By connecting the projections indicating an increase of water scarcity together with a wide acceptance towards the implementation of water reuse measures to face water scarcity, it is possible to infer that the number of these 'water scarcity – water reuse' (WS-WR) situations will grow. In this context, striving for water security means considering the entire situation as comprehensively as possible and in the long-term; not only focusing on the additional supply of water and efficiency offered by water reuse now but on the inherent imbalance between supply sources (freshwater and reuse) and demand (withdrawals). Therefore, comprehensively addressing WS-WR situations in alignment with a water security view means including both perspectives: *From* water by addressing water scarcity issues, and *through* water by addressing the supply of water resources via water reuse. It also means focusing on the quantity and management points proposed by Gain et al. (2016): quantity aspects are directly addressed by water scarcity; whereas, for the management point, the concepts of risk and sustainability can guide the views on water scarcity and water reuse, respectively. The next subsection provides the basic understanding of the concepts of risk and sustainability that allow identifying and delineating the research gap and objectives.

1.1.2 Risk and sustainability discourses for water-related decision-making

Addressing both perspectives of water security – *from* and *through* water – calls for considering both the risks associated with water-related disasters and the sustainability of adequate water supply, respectively. Both, risk and sustainability, are relevant concepts not only for water-related issues as they have been globally recognised to set agendas and guide decision-making across a variety of other sectors. The following brief overview of recent historical milestones shows how these concepts evolved from disciplinary topics of concern into structured guidance discourses[1].

After great losses due to natural disasters, in the 1960s, the General Assembly of the United Nations decided to coordinate funds and experts to assist countries in facing the negative impacts of such disasters (UNDRR n.d.). This action is later further established by creating a designated branch of the United Nations, the Disaster Relief Office (UNDRO). The approach towards disasters achieved a more organised structure between the 1970s and 1980s. Still, the position facing disasters was rather reactive, i.e., responding to the disaster and supporting the work of recovering from impacts (ibid.). This mindset changed in the 1990s via the International Decade for Natural Disaster Reduction (IDNDR) and its framework that directed the international community's attention to a more proactive view that focused on reducing impacts and increasing resilience (ibid.; e.g., Rossi 2000). This change in mindset was also accompanied by recognising the connection between sustainable development (see below) and disaster risk reduction (UN 1994). In the year 1994, the Yokohama Strategy and Plan of Action were endorsed and adopted, striving for formal risk assessments, disaster prevention and preparedness for policy and planning, the development and use of early warning systems, sharing technology, environmental protection, among other principles. By the end of that decade, the successor of the IDNDR was the

[1] *Discourse* is understood as "*a network of concepts, statements, and practices that collectively produce and authenticate particular knowledges and truths*" (Aylett and Barnes 2009, 153).

International Strategy for Disaster Reduction (UNISDR). After several achievements – especially for awareness-raising and multi-sectoral and interdisciplinary dialogues – five main gaps were identified related to governance; risk identification, assessment and monitoring; knowledge management and education; risk reduction; and preparedness for response and recovery (UN 2005). These gaps served as the core areas to develop the Hyogo Framework for Action 2005–2015 (ibid.). Following the effective results achieved by the different initiatives and frameworks, in 2015, the Sendai Framework for Disaster Risk Reduction 2015–2030 is adopted. This new framework sets seven global targets (Figure 1.1) and four priorities for action: *"(1) understanding disaster risk, (2) strengthening disaster risk governance to manage disaster risk, (3) investing in disaster risk reduction for resilience, and (4) enhancing disaster preparedness for effective response and to "Build Back Better" in recovery, rehabilitation and reconstruction*" (UN 2015a, 8). These targets and priorities aim at supporting the assessment of global progress towards achieving "*[t]he substantial reduction of disaster risk and losses in lives, livelihoods and health and in the economic, physical, social, cultural and environmental assets of persons, businesses, communities and countries*" (ibid., 6). Other important points regarding the recent global disaster-risk-related agenda are (a) the change of name from UNDRO – that already identified as UNISDR – to UN Office for Disaster Risk Reduction in 2019 (UNDRR n.d.); and (b) the definition of disaster risk as "*[t]he potential loss of life, injury, or destroyed or damaged assets which could occur to a system, society or a community in a specific period of time, determined probabilistically as a function of hazard, exposure, vulnerability and capacity*" (UNDRR n.d.) (more details in Chapter 2).

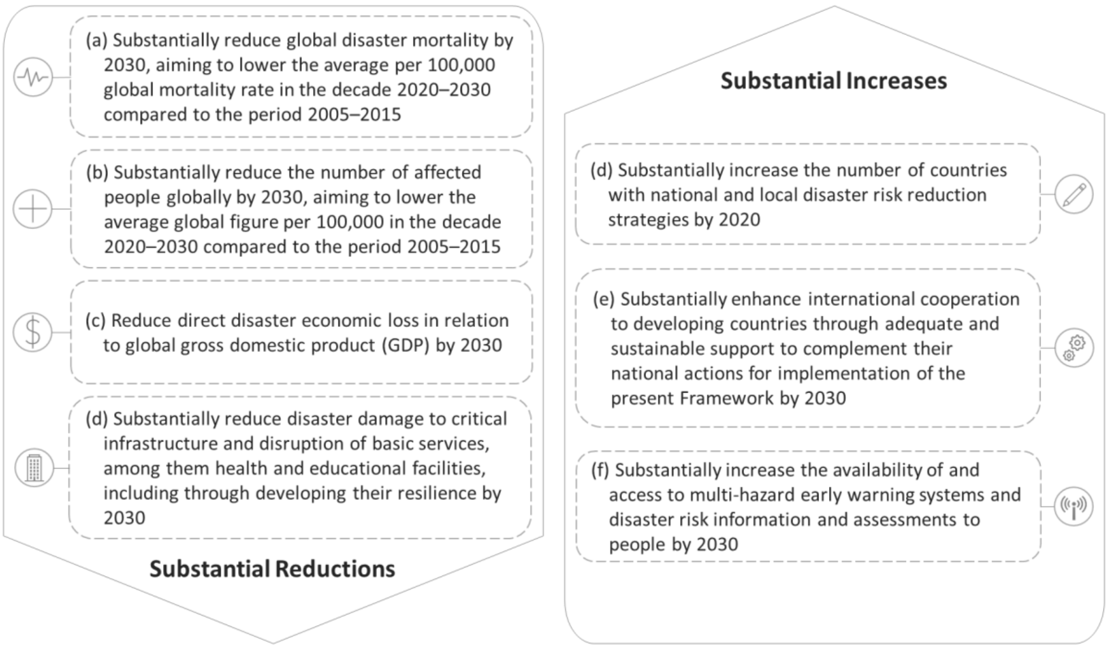

Figure 1.1: List of the seven global targets set in the Sendai Framework 2015–2030. Source: A/RES/69/283, 2015, p. 6 – based on UNDRR (n.d.).

The concept of sustainability was introduced already in the 17th and 18th centuries in the field of forest management, referring to "sustainable yield" as a way of facing deteriorating resources in Europe (Purvis et al. 2019). From there onwards, the meaning and use of this concept have morphed through time. In the early 19th century, the discussion focused on reconciling economic and social interests, namely wealth and social justice. Later on, discussions about conserving and preserving nature and natural resources became another key factor in fulfilling economic and social interests (ibid.). In the 20th century, the focus was on reconciling all discourses by understanding the relationship between the social, economic, and environmental aspects. The closeness between these dimensions became more apparent with recognising the finite character of the world we live in, i.e., through the discourse of "Limits to Growth" published in the 1970s (ibid.). By the 1980s, the understanding of social, economic, and environmental interests was converging. In 1987, the World Commission on Environmental Development published the report "Our Common Future" defining the relevance of sustainable development and what it entails (WCED 1987). This understanding was accepted by the General Assembly of the United Nations, agreeing that "*[h]umanity has the ability to make development sustainable to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs*" (UN 1987, 24). The key interests that had guided past discussions, namely, social, economic, and environmental – also known as the Triple Bottom Line or sustainability dimensions – guided now the operationalisation of the concepts "sustainable development" and "sustainability". The operationalisation facilitated setting global goals starting with the "Agenda 21" in 1992 with the focus of "*preparing the world for the challenges of the next century*" (UN 1992, 3). In 2000 the Millennium Development Goals (MDGs) set new goals with specific targets to achieve by 2015. Lastly, in 2015 the MDGs were replaced by the 2030 Agenda for Sustainable Development with 17 new Sustainable Development Goals (SDGs – Figure 1.2) and 169 targets (UN 2015b). This agenda shapes the goals around five areas (5 Ps) – people, planet, prosperity, peace, and partnership – in an "*indivisible manner*" to "*balance the three dimensions of sustainable development: the economic, social and environmental*" (ibid., 1). Thus, the concept of sustainability has evolved into a principle guiding decision-making.

Figure 1.2: Icons of the 2030 Agenda 17 Sustainable Development Goals (SDGs)

Essentially, risk and sustainability global agendas have been created to guide and support decision-making towards improving the living conditions of human beings. When comparing the evolution of both risk and sustainability discourses it is possible to visualise parallel paths and timing since the 1990s culminating with similar global agreements in 2015, i.e. the Sendai Framework for Action and the 2030 Agenda for Sustainable Development (see Figure 1.3). The particularity of these milestones is the mutual recognition of each guiding discourse and the relationship between risk and sustainability. Both concepts are explicitly recognised in the respective agendas, the Sendai Framework is explicitly mentioned in SDG11 (target 11.b) (UN 2015b), and sustainable development plays a central role in the Sendai Framework – SDGs are not explicitly mentioned in the Sendai Framework as they were endorsed months later (UN 2015a). However, this mutual recognition is still in its infancy when it comes to implementation. As stated in the 2019 Global Assessment Report on Disaster Risk Reduction "*Unlike HFA [Hyogo Framework for Action] and the Millennium Development Goals, implementation of the 2030 Agenda and its SDGs have now been linked with the Sendai Framework*" (UNDRR 2019, 31). Beyond timing, there are two main drivers for this link: the interest of reducing the reporting overlap and the recognition that the achievement of risk and sustainability objectives are mutually dependent (UNDRR 2019). These drivers have led the pursuit of a "risk-informed sustainable development", pushing towards improvements at a conceptual (e.g., understanding of risk) and operational (e.g., modelling tools, type and use of indicators) level as well as at a management level (ibid.). There is plenty of room for such improvements as the disctribution of data, metrics, and models is fragmented and sometimes inaccessible across a variety of sectors (ibid.). Likewise, risk and sustainability discourses have evidenced the complexity enabling the development of human life, i.e., how social and environmental well-being, and economic welfare are interconnected and should not be addressed in isolation or independently from each other. Thus, the abovementioned improvements need to be framed by simultaneously addressing social, economic, and environmental aspects of a risk situation that can threaten a sustainable development.

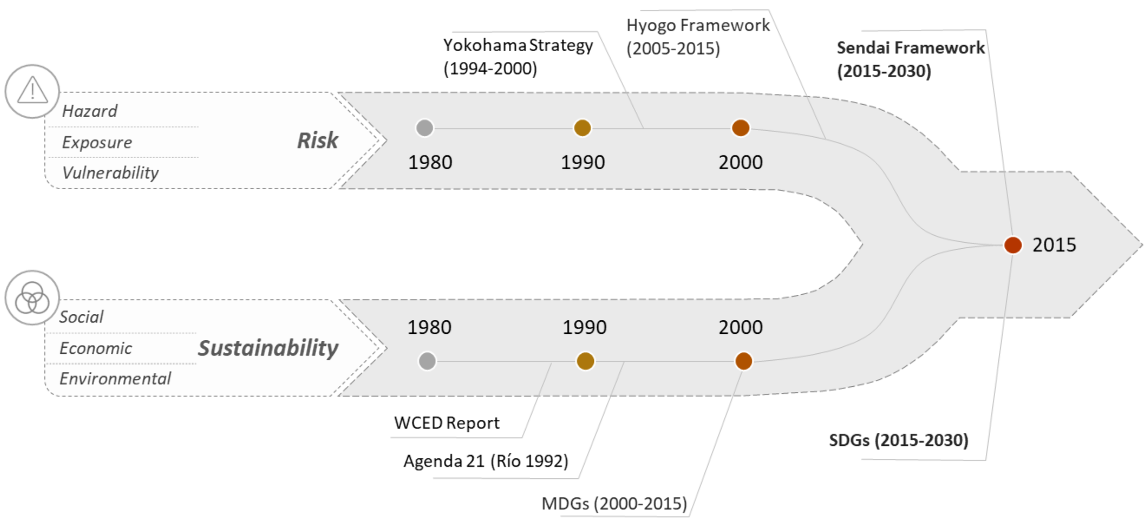

Figure 1.3 Risk and sustainability milestones of the past 40 years

For the specific case of water resources management, this interconnected view has also guided its development over the past 20 years. This has meant not only addressing water resources from the perspectives of risk and sustainability as done with 'water security', but also recoginising the role that water resources play in the development of other goods and services. Such is the case of Integrated Water Resources Management (IWRM), where despite a water-centric view, the management of water resources is not addressed in isolation. IWRM refers to "*a process which promotes the coordinated development and management of water, land and related resources in order to maximise economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems and the environment.*" (GWP 2000). The influence of the sustainability discourse becomes evident not only by its explicit mention but also by the clear role of its three dimensions. It is important to recognise that IWRM is an iterative process instead of a one-time event approach. There is no unique correct administrative model that fits all cases (GWP 2020). This concept has been explicitly included in the 2030 Agenda as part of SDG6 being target 6.5 (UN 2015b). Four dimensions ground its implementation (Table 1.1): enabling environmental, institutions and participation, management instruments, and financing (UNEP 2021). These dimensions are broad, referring to a variety of management aspects that highlight not only the legal, institutional, and financial requirements but also the relevance of data and information for decision-making.

Table 1.1: Dimensions to report the degree of implementation of IWRM as indicator 6.5.1 in the SDGs. Source: UNEP (2021).

Dimension	Focus*
Enabling Environment	*"In an enabling environment, national and subnational **policies and laws outline the importance of integrated approaches to water resources management**. Plans are needed to operationali[s]e policy and regulatory frameworks."*
Institutions and Participation	*"**Institutions**, and **stakeholder participation across sectors**, are needed at all levels to implement plans and enforce regulations."*
Management Instruments	*"**Data and information** need to be provided to all relevant stakeholders to allow **for informed decision-making**, covering aspects such as sustainable use, pollution control, ecosystem management and disaster risk reduction."*
Financing	*"**Budgets** at the national and local level, **for investments and ongoing infrastructure and management costs**, are needed to implement management instruments and fund institutions. **Revenue raising** is an important part of this."*

**Bold formatting of words is not part of the original text. It is used here to emphasise relevance for this section.*

Furthermore, Nexus thinking has expanded the integrated view to the relationship with other sectors producing different goods and services based on other resources (e.g., food production by the agricultural sector) (Bleischwitz et al. 2018; Itayi et al. 2021). This expansion aims at a decentralised view focused on the interconnections of sub-systems that have been otherwise developed and researched in a siloed manner (UNU-FLORES n.d.). Such is the case of the WEF nexus, linking water, energy, and food sectors with the focus of providing security to all of them (e.g., Chang et al. 2020). This young field of research focuses on studying the impacts of management decisions within one sector on other sectors and vice versa, identifying synergies and trade-offs via the study of interconnections and evidencing the complexity of tracking such impacts (Hoff 2011; UNU-FLORES n.d.). For instance, it is clear that the water sector requires energy for its functioning (supply of freshwater and sanitation and treatment of wastewater) while the energy sector often relies on water resources for energy generation; thus, a nexus perspective analyses the impacts of water management decisions on energy generation and the impacts of energy generation decisions on water resources.

When trying to understand the further implications of these decisions in both perspectives – water-centric (e.g., IWRM) or decentralised (e.g., Nexus thinking) – the relevance of how decisions are made is patent. Often in water-related decision-making, there is high uncertainty due to the consequences of measures and the perception of the involved actors (Sigel et al. 2010). Additionally, the '*ever-increasing size and pace of information flows that submerge decision-makers*' (Hugé et al. 2016) enhance the complexity of the decision-making process. Decisions have to consider and account for the interlinkages and interdependencies of the involved dimensions: social, economic, environmental (Wilcox et al. 2016), and technical aspects. There is no 'silver bullet' approach to address all considerations since the interests, goals and requirements arise according to the specific characteristics of the situation (ibid.). However, there are different ways of supporting decision-making to reduce the initial uncertainty and estimate potential outcomes and impacts. Decision support helps in providing a broader view of the situation, allowing the decision-maker to count with more information about the associated components, stakeholders, resources, and the interconnections between them, as well as the possible outcomes. This way the overwhelming amount of information can be better presented and processed to reduce the inherent uncertainty related to water resource management. As mentioned, decision-makers have to consider and account for different aspects of interest. These aspects – reflected in the sustainability dimensions, have their own terms, working fields and related specific interests, e.g., maximum economic profit, environmental and social wellbeing, technical feasibility, etc. and they relate to each other in various ways including through different institutional and organisational arrangements. When addressing a particulat situation, this means paying attention to its specific institutional and organisational context at that point in time. Additionally, decision-makers have to consider the perception and awareness of the community as well as their own. Thus, the situation involves: complex and dynamic biophysical settings with the involved uncertainties and change in matter and energy fluxes, and the resulting multi-actor constellations across different sectors engaging in diverse information exchanges under varying institutional and organisational contexts. The results is a complex situation with dynamic, uncertain and non-linear interlinkages. In order to address this complexity, decision support aims at assisting the decision-making process by handling and facilitating, in an organised manner, the input and output of information for better analysis and evaluation.

1.1.3 Problem statement and research focus

The World Water Assessment Programme has recognised that "*[…] water is multidimensional and essential for human well-being, economic and social activities, energy and food production, and the maintenance of ecosystems, a multitude of institutions are involved in its management*" (WWAP 2018, 41). This essentiality and multidimensionality complicate appropriate management.

The previous sections provided a glimpse of three main factors: (a) the expected increase in the number of WS-WR situations, (b) the call for improving management instruments such as assessments to support decision-making, and (c) the key role of information for decision-making with a growing interest of processing it in a comprehensive and integrated manner. Thus, there is potential of further advancing existing risk and sustainability management instruments for WS-

WR situations, i.e., how to process information in an integrated manner to support decision-makers in these situations.

Figure 1.4 shows a schematic view of the focus of this research encompassed by the broader context of water resources management. Among the concerns of water management for water security, namely, quantity, quality and accessibility of/to water resources, this work focuses on the quantity aspects as it addresses the issue of water scarcity. Within the alternatives to tackle this issue – supply and demand – this work focuses on increasing water supply and, out of these alternatives, water reuse measures. These focus points set the conceptual boundaries and requirements of the integrated assessment: risk of water scarcity and sustainability of water reuse. As an initial approach towards integration of risk and sustainability in WS-WR situations, and because water scarcity mainly refers to quantity aspects, quality and accessibility may be mentioned but do not belong to the core of this research.

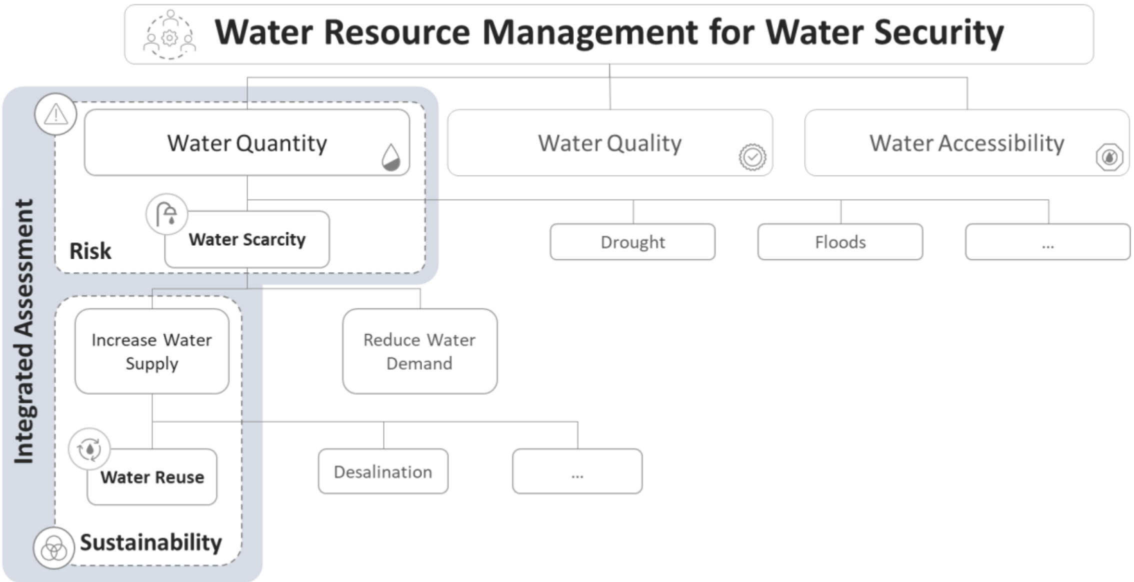

Figure 1.4: Schematic view of the focus of this research within water resources management

1.2 Objectives and research questions

This research is primarily qualitative with a generative and exploratory character as it aims at providing new ideas for the integration of risk and sustainability for the case of WS-WR situations. Three objectives specify this aim and directly link to three research questions as presented in Figure 1.5.

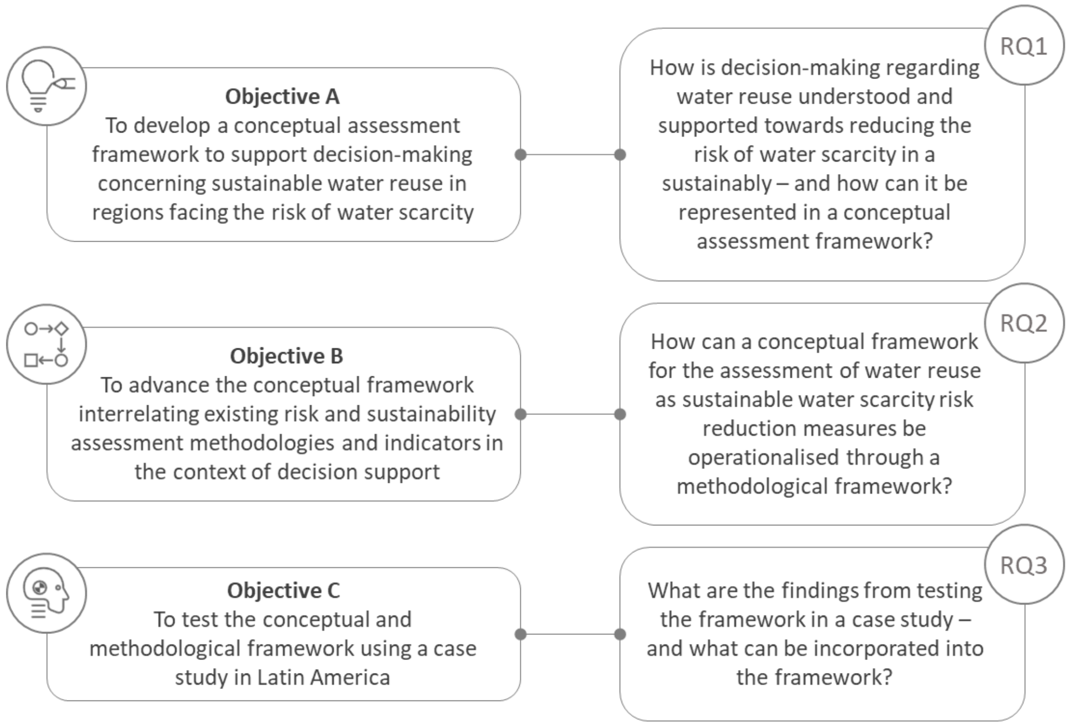

Figure 1.5: Objectives and research questions (RQs)

1.3 Research approach and structure of the document

1.3.1 Research approach

The three objectives guide the flow of the research approach following a deductive to inductive rationale. Accordingly, the approach encompasses three broad stages for the development of an integrated Risk and Sustainability Assessment (RSA) Framework (output) to support decision-making in WS-WR situations: (i) developing the conceptual framework, (ii) advancing the methodological aspects, and (iii) testing the framework (Figure 1.6). A deductive approach guides the development of the integrated RSA Framework in both the conceptual framework and methodological aspects, whereas the testing of the framework allows an inductive learning process. The research approach also relies on feedback connecting each stage. The conceptual work delineates the methodological aspects, which, when advanced, can provide valuable feedback to incorporate into the conceptual framework. Likewise, the testing step provides the opportunity to gather learnings of a real-world implementation in a case study that helps reflect on the applied methods and, ultimately, the designed conceptualisation.

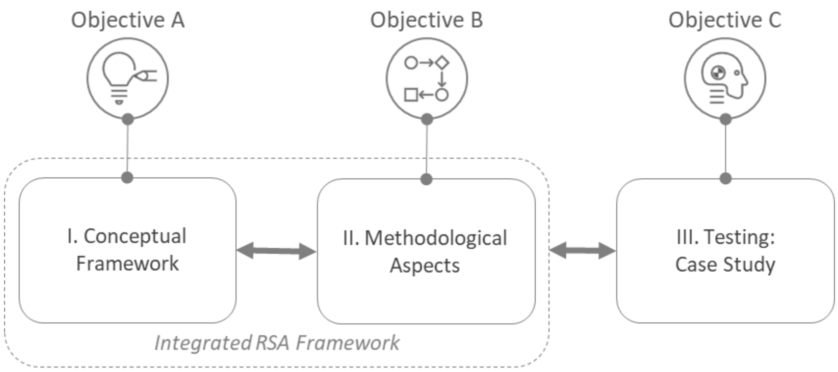

Figure 1.6: Research approach according to the objectives

1.3.1.1 Conceptual framework

The conceptual framework development consists of revising different theories, frameworks, and definitions of relevant concepts, connecting them, and structuring the integrated RSA framework. The analysed concepts are: 'water scarcity', 'water reuse', 'risk', 'sustainability', and 'decision-making'. These definitions and their integrative interpretation allow building a conceptual framework with clear and integral roles for the involved concepts. The result is an integrated Risk and Sustainability Assessment (RSA) Framework for WS-WR situations comprising analysis and evaluation phases.

1.3.1.2 Methodological aspects

This step of the research approach aims at advancing the conceptual framework by operationalising the analysis and evaluation phases. However, because the development of the conceptual framework resulted in identifying a greater gap on the analytical side, the methodological aspects, while incorporating the evaluation phase, focus on advancing the analysis of information to be evaluated by the RSA assessment. The result is the proposal of an analytical concept to organise and process the relevant information. This concept relies on (1) a multi-layer approach (ML) as a means of translating a biophysical-systems-view of the situation to an indicator-based information system; and (2) a lane-based approach to identify and characterise interlinkages between social, economic, and environmental aspects as well as between risk and sustainability perspectives. The analytical concept intends to bridge the aim of the RSA with the evaluation phase, providing an aligned operationalisation from the beginning of the assessment.

1.3.1.3 Framework testing

The testing builds on both the conceptual and methodological aspects to carry out the analysis and evaluation of the WS-WR situation in a case study. The aim is to apply the integrated RSA framework in a case study to identify gaps and improvement points. The case study is situated in Latin America, in a location meeting the requirements of a WS-WR, i.e., facing water scarcity and either planning to implement or already counting on an implemented water reuse measure.

Latin America possesses an interesting water resources management context characterised by a heterogeneous distribution of water resources and a contrasting sanitation and treatment coverage. Latin America represents slightly less than 15% of the global terrestrial surface but receives around 30% of the worldwide precipitation in a year (FAO 2017). At first sight, this would mean that there are no issues concerning water security in the region. However, due to great climatic variability, the distribution of the available water resources varies significantly (ibid.). In addition, high demographic and urbanisation rates have led to a situation of water scarcity that is affecting millions of persons (Ballestero et al. 2015). In South America only, projections indicate that around 82.5 million people will live under perennial and seasonal water scarcity conditions in 2050 (He et al. 2021). Within this southern area, regions in Argentina, Peru and Chile have been and will continue to be severely affected by perennial water scarcity (Luo et al. 2015; Mekonnen and Hoekstra 2016).

The value of water reuse is recognised throughout Latin America as there are already established practices, mainly for agricultural irrigation and especially in areas undergoing water scarcity (FAO 2017). However, as well as the water resource distribution, there is great variability between countries to treat household wastewater safely (Figure 1.7). UN-Habitat and the World Health Organisation report that Latin America treats 40.8% of the produced household wastewater (2021). Contrastingly the FAO and the Development Bank of Latin America (CAF) mention that despite the installed capacity to treat such amounts, due to operational problems, the proportion of wastewater that is effectively treated is substantially lower, possibly around 20% (Ballestero et al. 2015; FAO 2017). The issue related to the installed WWTPs is that plenty of them are not operative or not working correctly because of a lack of adequate management and abandonment (ibid.). The current situation presents a barrier when aiming towards the use of treated wastewater since without working WWTPs, the quantity and quality of the treated wastewater are low. In 2015, the CAF recognised that solutions to face water scarcity in Latin America rely importantly on improving the management of the water sector companies (CAF 2015). Thus, despite this challenging situation, there is the opportunity of changing the view towards focusing on the sustainability of water reuse measures to avoid repeating the current situation surrounding the WWTPs.

In summary, Latin America represents a territory with areas affected by water scarcity showing a need to implement new water resources management strategies. This means that decision support can be of great importance. These aspects make Latin America an interesting region to test the integrated RSA framework for WS-WR situations.

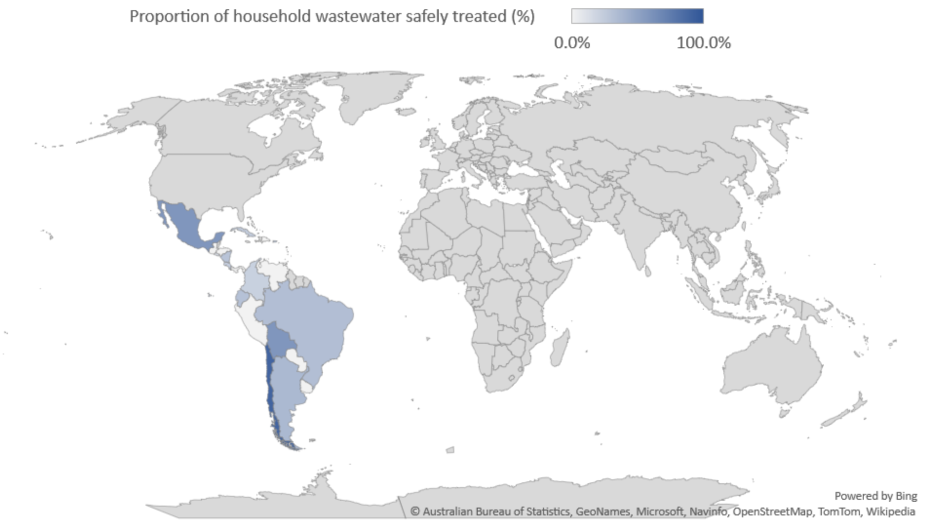

Figure 1.7: Proportion of household wastewater safely treated in Latin America. Source: UN-Habitat and WHO (2021).

1.3.2 Structure of the document

The structure of this document follows the abovementioned objectives and research approach, as shown in Figure 1.8. Each chapter subsequently builds on the provided content via three scientific articles that support this cumulative dissertation:

Article 1. **Müller, Andrea B.**, Tamara Avellán, and Jochen Schanze. 2020. 'Risk and Sustainability Assessment Framework for Decision Support in "Water Scarcity – Water Reuse" Situations'. Journal of Hydrology 591 (December): 125424. https://doi.org/10.1016/j.jhydrol.2020.125424.
Authors retain the right to include this publication in a thesis or dissertation.

Article 2. **Müller, Andrea B.**, Tamara Avellán, and Jochen Schanze. 2022. 'Translating the "Water Scarcity – Water Reuse" Situation into an Information System for Decision-Making'. Sustainability Science 17: 9–25.
https://doi.org/10.1007/s11625-021-01077-9.
Open Access article, licensed under a Creative Commons licence.

Article 3. **Müller, Andrea B.**, Christy Bennett, Tamara Avellán, and Jochen Schanze. 2023. 'Testing the Integrated Risk and Sustainability Assessment (RSA) Framework for 'Water Scarcity – Water Reuse' Situations: The Case of Cerrillos de Tamaya, Chile'. Current Research in Environmental Sustainability 5: 100203.
https://doi.org/10.1016/j.crsust.2022.100203.
Open Access article, licensed under Creative Commons Licence.

The current chapter presents the background information to understand the motivation core concepts of this research that sustain the three objectives and their respective research questions, which guide and structure the flow of this document. Chapter 2 addresses the development of the conceptual framework (objective A and RQ1). This chapter corresponds to the scientific article 1. Chapter 3 refers to the methodological aspects (objective B and RQ2). This chapter corresponds to the scientific article 2. Chapter 4 presents the work done to test the framework (objective C and RQ3) in a case study of a WS-WR situation in northern Chile. This chapter corresponds to the scientific article 3. Chapter 5 summarises key results and findings of the previous chapters that support the synthesis and discussion of crosscutting aspects. This chapter places the developed framework in a broader context. Chapter 6 includes the concluding remarks to the achievement of the objectives and the responses to the RQs, framing existing limitations and providing an outlook of this research. The Annexes include the supplementary material (S or SM, accordingly) of the scientific articles.

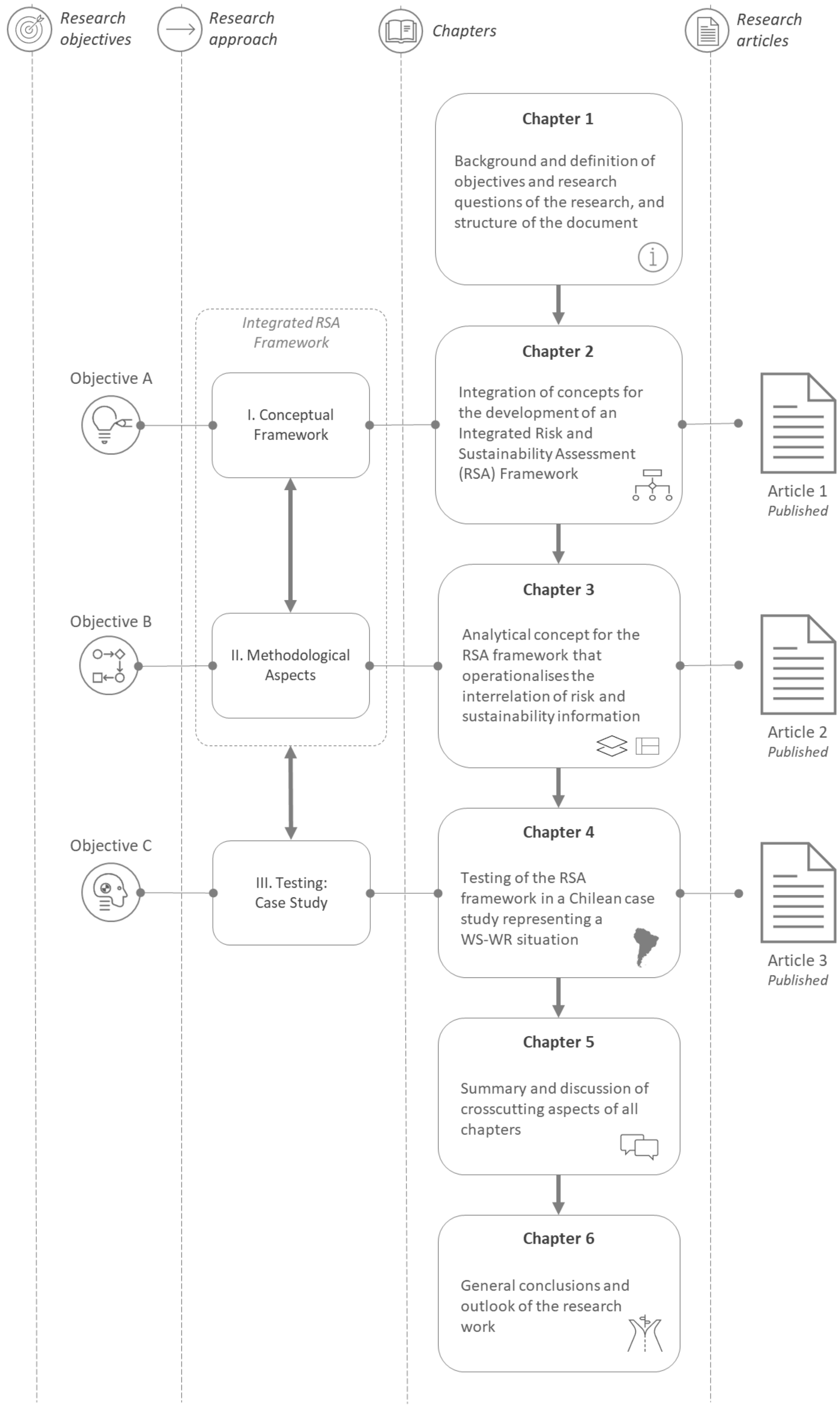

Figure 1.8: Schematic representation of the chapters of this document, their content and alignment with the research objectives and approach.

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Chapter 2 Conceptual Framework

This chapter corresponds to the published scientific article 1 (see sub-section 1.3.2). It addresses the development of the conceptual framework based on a three-step approach: (i) definition and interpretation of the subject at stake, (ii) identification and description of key concepts, and (iii) construction of the conceptual framework. As such, it focuses on:

- Defining the concepts of water scarcity, water reuse, risk and risk assessment, sustainability and sustainability assessment, and decision-making.
- Integrating the concepts by interpreting water scarcity from a risk perspective and water reuse from a sustainability perspective, and how assessments support decision-making.
- Structuring the assessment based on the understanding of the decision-making process, the risk assessment configuration (analysis and evaluation), and the sustainability social, economic, and environmental dimensions.

Risk and sustainability assessment framework for decision support in 'water scarcity – water reuse' situations

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Abstract

Decision-makers face major challenges when trying to reduce risks of water scarcity sustainably through measures of water reuse. One of these challenges is the lack of interconnectedness between risk assessment for water scarcity and sustainability assessment for water reuse. Therefore, this paper aims to explore the conceptual integration of risk and sustainability assessments (RSA) in a framework for decision support in 'water scarcity – water reuse' situations. This article follows a three steps approach: (i) defining and interpreting the 'water scarcity – water reuse' situation as a coupled human and natural system; (ii) identifying and defining key concepts relevant for risk and sustainability assessment, and (iii) constructing the integrated RSA Framework for decision support. As a result, the latter provides a conceptualisation of a simultaneous assessment of water scarcity as a risk and the sustainability of water reuse measures according to the social, economic, and environmental dimensions. It contemplates an analysis phase and an evaluation phase to provide unified information on the level of water scarcity risk and water reuse sustainability. The resulting indicates that the integration of risk and sustainability in one joint assessment for decision support is conceptually feasible. It hence paves the way towards a comprehensive and consistent methodological operationalisation and empirical application.

Keywords: water scarcity, water reuse, risk reduction, sustainability, decision-making, integrated assessment

Graphical abstract

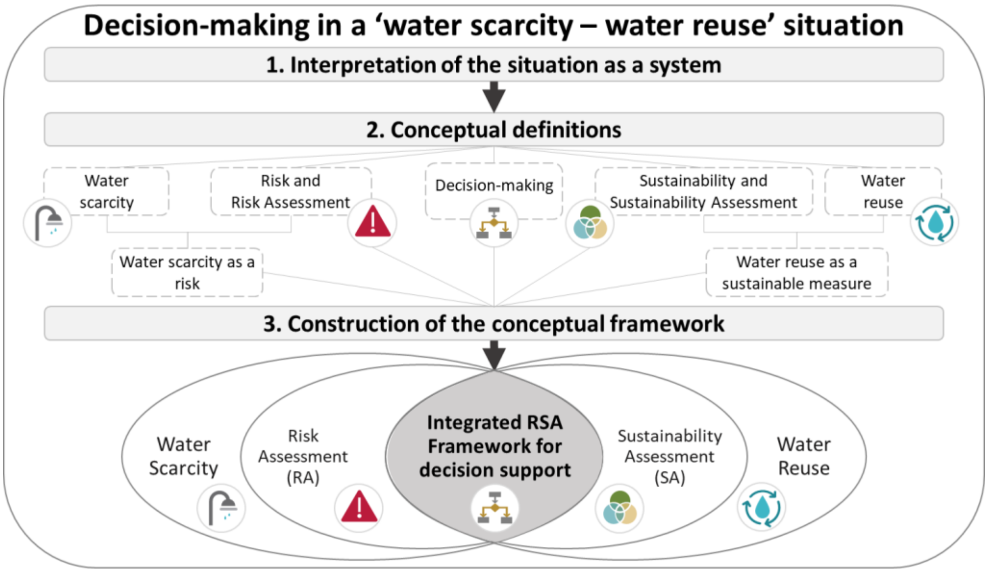

Figure 2.1: Graphical abstract

2.1 Introduction

Achieving water security is key for sustainable development (United Nations 2015). Water security may be achieved by managing water resources in a way that they are accessible, in an appropriate quantity and quality for human uses while respecting water as integral part of ecosystems (e.g., GWP 2000; Schulte and Morrison 2014). But, water resources are increasingly stressed in their quantity and quality by demographic development, economic growth and climate change, which is likely to lead to a severe global water crisis (Alcamo et al. 2007; Kumar et al. 2018). Over 1.7 billion people live in river basins where withdrawal exceeds recharge (UNDP 2016); by 2050 70% of the river basins are projected to suffer water-related problems with more than four billion people living in cities with persistent or seasonal water scarcity (Alcamo et al. 2007; McDonald et al. 2011; WWAP 2018). The world is, therefore, far from being water secure.

Water reuse or using treated wastewater for diverse purposes is heavily discussed as a means of increasing available water quantities at diverse quality ranges and thus lowering freshwater withdrawals to alleviate water scarcity (WWAP 2017; Gancheva et al. 2018). Fit-for-purpose production and the use of this kind of water are certainly not the only means of overcoming water scarcity since there are other alternatives including desalination, inter-basin water transfer, and water withdrawal restriction. However, water reuse is seeing a particularly increased implementation in regions facing apparent water scarcity, generating 'water scarcity – water reuse' situations (e.g., Asano et al., 2007; Levy et al., 2014; FAO, 2017; Voulvoulis, 2018). Water reuse in these regions is also specifically advocated as a sustainable measure to overcome water scarcity (Bedbabis et al. 2010; Wilcox et al. 2016; El Moussaoui et al. 2017; Fito and Van Hulle 2020). Hence, the current discourse in scientific and grey literature seems to advocate for water reuse as a sustainable measure to overcome the risk of water scarcity.

So far, much needed attention is being paid on the risks related to the quality of the used water and how to mitigate, reduce and circumvent these (e.g., WWAP 2017; DWA 2019). The contribution of water reuse measures to the reduction of water scarcity risk has not been a major topic yet. One reason seems to be that water scarcity and water reuse are mostly tackled in two different realms of water management responding to different aims. While water scarcity is a subject of natural disaster risk management to identify and reduce the level of risk; water reuse evolved in water resources management with the aim of long-term assurance of water availability in adequate quality, i.e. to support a sustainable water resource management. Each realm has distinct conceptual and methodological approaches and these differences make it particularly challenging for an integration that supports decision-making (UNISDR 2015), in this case, on water scarcity risk reduction through sustainable water reuse. There are approaches for risk assessment to deal with water scarcity on the one hand (e.g., Veldkamp et al. 2016) and sustainability assessment of water reuse measures on the other hand (e.g., Akhoundi and Nazif, 2018). While risk assessment related to water scarcity highlights issues of water shortage (e.g., WEF Global Risk Report 2019) and in water supply (e.g., World Risk Report by Mucke et al. 2019), water-related sustainability assessments provides information focusing on social, economic and environmental aspects of water management measures such as water reuse (e.g., Opher et al. 2019; Rezaei et al. 2019). Aspects such as whether there will be enough quantity of water water resource as well as knowing about the water scarcity situation have been reported as relevant success factors for the implementation of water reuse measures (Mainali et al. 2011; Tran et al. 2017). Such information can be provided by a risk assessment of water scarcity. Likewise, considering a lesson learnt after the Hyogo Framework for Action 2005-2015 (UNISDR 2015) taken by the Sustainable Development Goals (SDGs, i.e. SDG 11) (United Nations, 2015a), there is the need for integrating risk and sustainability approaches in general.

Thus, before a decision-maker tackles the challenging question of which kind of measure to use to reduce the risks from the quality of treated wastewater, it may make sense to first assess if any of the considered water reuse measures would actually sustainably reduce the main risk, namely that of water scarcity. If this is not the case, other measures to do so may have to be sought. Currently, assessment approaches considering simultaneously both aspects, that of a risk and a sustainability assessment, are lacking.

Therefore, this research aims at developing a framework that conceptually integrates risk assessment and sustainability assessment for decision support in ‘water scarcity – water reuse’ situations. The intention of the framework is to ensure an appropriate joint consideration of the risk of water scarcity and the sustainability of water reuse as a measure for risk reduction. This provides the basis for a subsequent assessment of water quality risk. The intended integrated Risk and Sustainability Assessment (RSA) Framework is designed to be applied in an (a) *ex ante* manner to support decisions related to whether a water reuse measure should be implemented given a measured or projected risk of water scarcity and what would be required to do this sustainably; or (b) *ex post* manner providing information about the risk of water scarcity and the sustainable performance of an already implemented water reuse measure. Both *ex ante* and *ex post* assessments are focused on water reuse measures, including comparative assessments between different system arrangements and technologies, but a comparison of water scarcity risk reduction measures beyond water reuse exceeds the scope of this work.

The reader may expect a conceptual work focused on the water quantity aspects of water management, integrating water scarcity risk assessment and water reuse sustainability assessment in a decision support framework. A detailed reflection on water quality and accessibility issues would transcend the scope of this work. Section 2.2 describes the approach for the development of the framework using a three-step procedure. Section 2.3 presents the results and discussion comprising (i) the system analysis of 'water scarcity – water reuse' situations, (ii) systematisation and explanation of concepts relevant for this framework, and finally (iii) the integrated RSA Framework for decision support. Moreover, this section refers to the comprehensiveness, specificity, and limitations of the framework. Section 2.4 provides conclusions and an outlook on future research demands particularly referring to methodological implementation.

2.2 Developing the conceptual framework

The use of conceptual frameworks is common in the environmental sciences, especially in the context of comprehensive analysis or management of natural resources (e.g., Berrouet et al., 2018; Pavan and Ometto, 2018). However, despite their fundamental role, not much detail is given about the approaches and steps followed for the construction of such frameworks. Jabareen (2009) offers a clear reflection on the meaning and analysis of conceptual frameworks. Accordingly, conceptual frameworks bear on the following core characteristics (ibid.):

i. "*a construct where each concept plays an integral role*";
ii. "*interpretative approach to social reality*";
iii. "*understanding*" rather than "*theoretical explanation*";
iv. "*interpretation of intentions*" rather than "*knowledge of hard facts*";
v. "*indeterministic in nature and therefore do not enable [us] to predict an outcome*";
vi. "*developed and constructed through a process of qualitative analysis*";
vii. "*the sources of data consist of many discipline-oriented theories that become the empirical data of the conceptual framework analysis*".

These characteristics are highly interwoven. For example, conceptual frameworks provide an "*interpretative approach to social reality*" while also being an "*interpretation of intentions*" which may not "*predict an outcome*". These characteristics and the analysis phases proposed by Jabareen allow for the derivation of three steps for the development of conceptual frameworks: (i) definition and interpretation of the subject at stake; (ii) identification and description of key concepts; and (iii) construction of the conceptual framework. Figure 2.2 depicts a schematic view of the approach as well as a preview of the obtained results (presented in section 2.3) to understand the structure of this article. The following subsections present more details about the three steps and their use for the development of the integrated Risk and Sustainability (RSA) Framework for decision support.

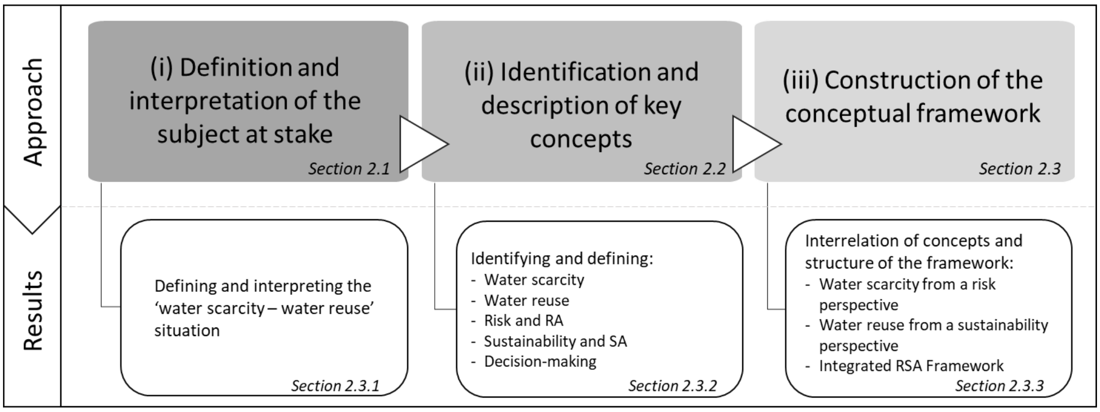

Figure 2.2: Schematic view of the approach and obtained results for the development of the integrated RSA Framework. RA: risk assessment; SA: sustainability assessment; RSA: risk and sustainability assessment.

2.2.1 Definition and interpretation of the subject at stake

The subject at stake is the decision-making in 'water scarcity – water reuse' situations with special focus on water quantity matters. These situations refer to actors, e.g., in a municipality, which expect to face or currently face water scarcity and who are planning to or have already implemented water reuse measures (see Figure 2.3). The aim is to support *ex ante* assessments related to the design, planning and implementation of future water reuse measures or *ex post* assessments related to the performance, control and monitoring of implemented water reuse measures. Both perspectives can support design, planning and implementation aspects to reduce the risk, increase the sustainability or even correlate the level of risk and sustainability. In all these cases, decision-makers exhibit an interest in reducing water scarcity by implementing sustainable water reuse measures.

Assessments play a key role in decision support by operationalising the topic they aim to asses (Alcamo et al., 2003). For the above mentioned 'water scarcity – water reuse' situations, risk assessment of water scarcity inform about the level of risk and how this could change (i.e. scenarios) or be reduced (e.g., Gain and Giupponi 2015; Veldkamp et al. 2016). In contrast, sustainability assessments can be used to compare different water reuse measures or portfolios of those measures, (e.g., Benavides et al. 2019; Opher et al. 2019; Rezaei et al. 2019). While risk assessment does not address the sustainability of alternative measures, a sustainability assessment does not comprise the water scarcity risk reduction effects of water reuse measures. Each of these assessments supports a particular decision and are not necessarily interrelated. But this distinction can inhibit comprehensiveness of decisions (see Figure 2.3a). However, since both assessments have succeeded in providing the respective information for decision-making, the focus of an advanced assessment here is set on further interrelating them. Therefore, the integrated RSA Framework intends to offer a structured and aforethought approach for addressing risk and sustainability simultaneously in a unified manner from the beginning. This is supposed to bridge data and information throughout the decision-making process for the delivery of comprehensive and consistent information rather than to converge results of two different assessment processes (see Figure 2.3b).

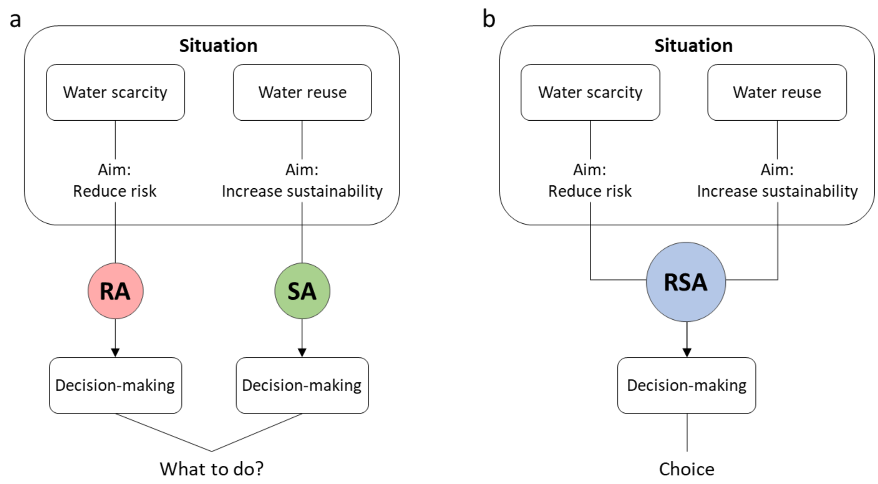

Figure 2.3: Presentation of a 'water scarcity – water reuse' situation considering either (a) independent decision-making or (b) the proposed integrated approach. RA: Risk Assessment. SA: Sustainability Assessment. RSA: Risk and Sustainability Assessment.

To gain a deeper understanding of a 'water scarcity – water reuse' situation, there is a need for interpreting it first. This should lead to a simplified representation that helps to reduce the complicatedness of the real-world situation and hence facilitate its understanding. Systems thinking allows addressing this complicatedness by interpreting situations as a "*set of interconnected parts which function together as a complex whole*" (Smithson et al. 2008, 9). In general, natural or environmental systems (e.g., ecosystems, hydrological systems) are originally conceptualised separate to societal systems (e.g., social organisational systems) (Smithson et al. 2008; Jalilov et al. 2018). However, for water management and related risk and sustainability studies, there is a particular interest in the interrelations between both systems (Turner et al. 2003; Ostrom 2009; Binder et al. 2013; Srinivasan et al. 2013; Schanze 2016). Therefore, the interpretation of a 'water scarcity – water reuse' situation needs to follow a systemic approach, in this case as a coupled human and natural system (CHANS) (Liu et al. 2007). This way, the system should consider and describe interrelations in form of energy, matter, and information flows (ibid.). The approach used for analysing the 'water scarcity – water reuse' situation distinguishes between a natural (or environmental) sub-system referring to biophysical aspects of matter and energy flows, whereas the human sub-system covers biophysical aspects on the one hand and immaterial aspects related to information flows on the other. In a 'water scarcity – water reuse' CHANS focused on water quantity, the biophysical system comprises the natural sub-system and the biophysical aspects of the human sub-system. In addition, considering the decision-making process for structuring the assessment requires involvement of the immaterial aspects of the human sub-system. In the respective CHANS, examples of elements related to the biophysical human aspects can include water withdrawal facilities, water supply infrastructure, sanitation, wastewater treatment plants, irrigation equipment; whereas immaterial elements may refer to e.g., the organisation of water resources management and the institutional arrangements such as legal regulations and governance modes (see Figure 2.4).

In general, systems analysis may involve qualitative or quantitative methods (Liu et al. 2007). A qualitative approach is used for the development of the integrated RSA Framework with the potential of quantitative analyses in subsequent research.

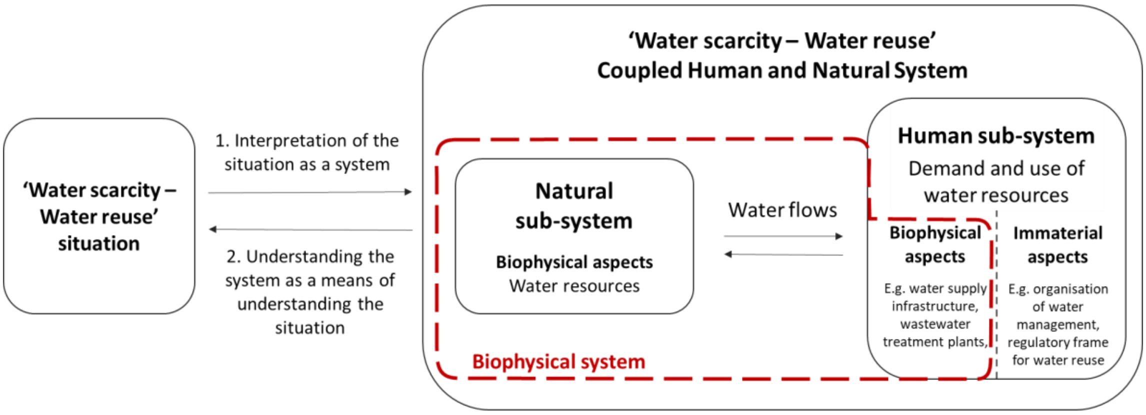

Figure 2.4: Tackling the 'water scarcity – water reuse' situation as a coupled human and natural system.

2.2.2 Identification and definition of key concepts

To further conceptualise the 'water scarcity – water reuse' situation and develop the integrated RSA Framework, it is important to define the following key concepts: 'water scarcity'; 'water reuse'; 'risk'; 'sustainability'; and the respective 'assessments'. Additionally, understanding 'decision-making' is required for tailoring the integrated assessment towards decision support. The reflection of all these concepts is relevant for overcoming misunderstandings in this interdisciplinary space, primarily because the way of understanding these concepts influences the preferred type of assessment (Tarne et al., 2017; see Section 2.3.2).

A non-systematic literature review involving academic and grey literature of these concepts is carried out to collect and contrast definitions from different disciplines and sectors to derive a coherent understanding. The definitions found in documents of international organisations (e.g., FAO, UNISDR, ISO) as well regulations (e.g., in the European Union), were assumed to represent a common transdisciplinary understanding of each concepts, as far as they are supported by the scientific literature. Section 2.3.2 presents the results of this review for the derivation of the working definitions of the mentioned concepts relevant for the framework.

2.2.3 Construction of the conceptual framework

After interpreting the situation and defining the relevant concepts there is the need of interrelating them to build the integrated RSA Framework. In this research, it involves the following steps:

1. Interrelating water scarcity with risk and water reuse with sustainability. This means using the risk and sustainability concepts to interpret the definitions of water scarcity and water reuse, respectively, as well as analysing potential risks for the sustainability of the water reuse measure.
2. Relating risk and sustainability assessments with each other and with decision-making. This addresses the alignment of the integrated assessment to decision-making, focusing on the common scope of the assessment and what it comprises (e.g., structure, procedure, indicators).

2.3 Results and discussion

The approach followed in this research facilitated a situational focus of the framework for the water-related situation, an open search of definitions of the relevant concepts and a structured interrelation of these concepts to create the framework. The results are conceptual and intend to provide the basis for methodological operationalisation and empirical studies involving existing methods and real-world data.

2.3.1 Defining and interpreting the 'water scarcity – water reuse' situation

According to section 2.2.1, the 'water scarcity – water reuse' situation may be interpreted as a coupled human and natural system (CHANS). This system comprises, on the one hand, natural and human biophysical aspects involving water flows and, on the other hand, immaterial aspects of water management decision-making with its institutional context. Individual elements need to be defined and interrelated to support decision-making on water scarcity risk reduction and sustainable water reuse. The interconnection between the biophysical system and the immaterial aspects of the human sub-system is given by the management alternatives that have an effect on the water flows (biophysical aspects) while resulting from the decision-making process, based on immaterial aspects (e.g., regulatory frame). Figure 2.5 shows the simplified representation of the system understanding.

The biophysical system that portrays the water flows consists of elements of the natural sub-system (e.g., the catchment area, ecosystems) and biophysical aspects of the human sub-system (e.g., withdrawal, supply, sanitation and treatment facilities, reuse). Different shapes classify these elements as: natural or human processes (sequence of change steps or activities resulting in natural or human outputs), products (goods) and users (that make "*-deliberate- application or utilisation of water for a specific purpose*"; FAO, n.d.). The classes refer to elements that have associated influences on the quantity of water (e.g., IWA, 2016).They are related to the water flows which in turn depend on climatological and hydrological conditions as well as the water management.

Moreover, it is possible to distinguish the water flow system in four main categories: source (freshwater resource); use (human use of water); treatment (sanitation and the treatment process); and reuse (human use and discharge of the treated wastewater and generated by-products). This categorisation helps relating the elements of the source and use categories to the water scarcity aspects of the situation, and the components of the treatment and reuse categories to water reuse. The reuse directly refers to elements of water use, but it is presented in a separate category to schematically highlight that it is the use of treated wastewater and not of freshwater. Therefore, there is a circular idea of water flows presented linearly. Such compartmentalised interpretation supports the understanding of the situation by providing the decision-maker with a general overview while considering relevant elements and their interrelations.

The immaterial aspects of the human sub-system focus on the information flows that result in the selection of management alternatives. They comprise the decision-makers (actors involved in the decision-making process e.g., a mayor), further stakeholders involved (e.g., civil society, NGOs), as well as the institutional and organisational context. The institutional and organisational context can define how decisions are made based on societal rules that structure social interactions (Redlawsk and Lau 2013), e.g., regulations referring to water reuse practices. However, there are information flows between the various institutional and organisational arrangements and to the different decision-makers and stakeholders. Likewise, there is a constant exchange of information between the decision-makers and with stakeholders. This exchange, is not necessarily uniform between the persons and groups involved, and hence can generate information and power asymmetries (e.g., Loch et al. 2014; Avellán et al. 2019; Pan et al. 2019). A proper representation of all actors and stakeholders requires specific stakeholder mapping and analysis according to social science methods (e.g., Mitchell et al., 1997; Reed et al., 2009). Although all immaterial aspects are situational, they are presented in a generic manner in Figure 2.5 for schematic reasons.

Finally, decision-making is summarised in one general box referring to water scarcity risk reduction and sustainable water reuse (the defined aim for this framework) and directly linked to the design of potential (*ex ante* assessment) or the performance control of existing (*ex post* assessment) management alternatives.

Overall, the 'water scarcity – water reuse' situation exceeds natural and engineering science boundaries and links to the social sciences, here particularly referring to decision theory, but beyond also several actor, stakeholder and network theories. A CHANS representation allows to portray not only matter flows (water) but also basic societal information flows simultaneously and hence precisely meets the requirements of the subject of the framework. Although any 'water scarcity – water reuse' situation has its site-specific character, this first general conceptualisation serves as basis for adaptation and refinement with a consistent level of detail.

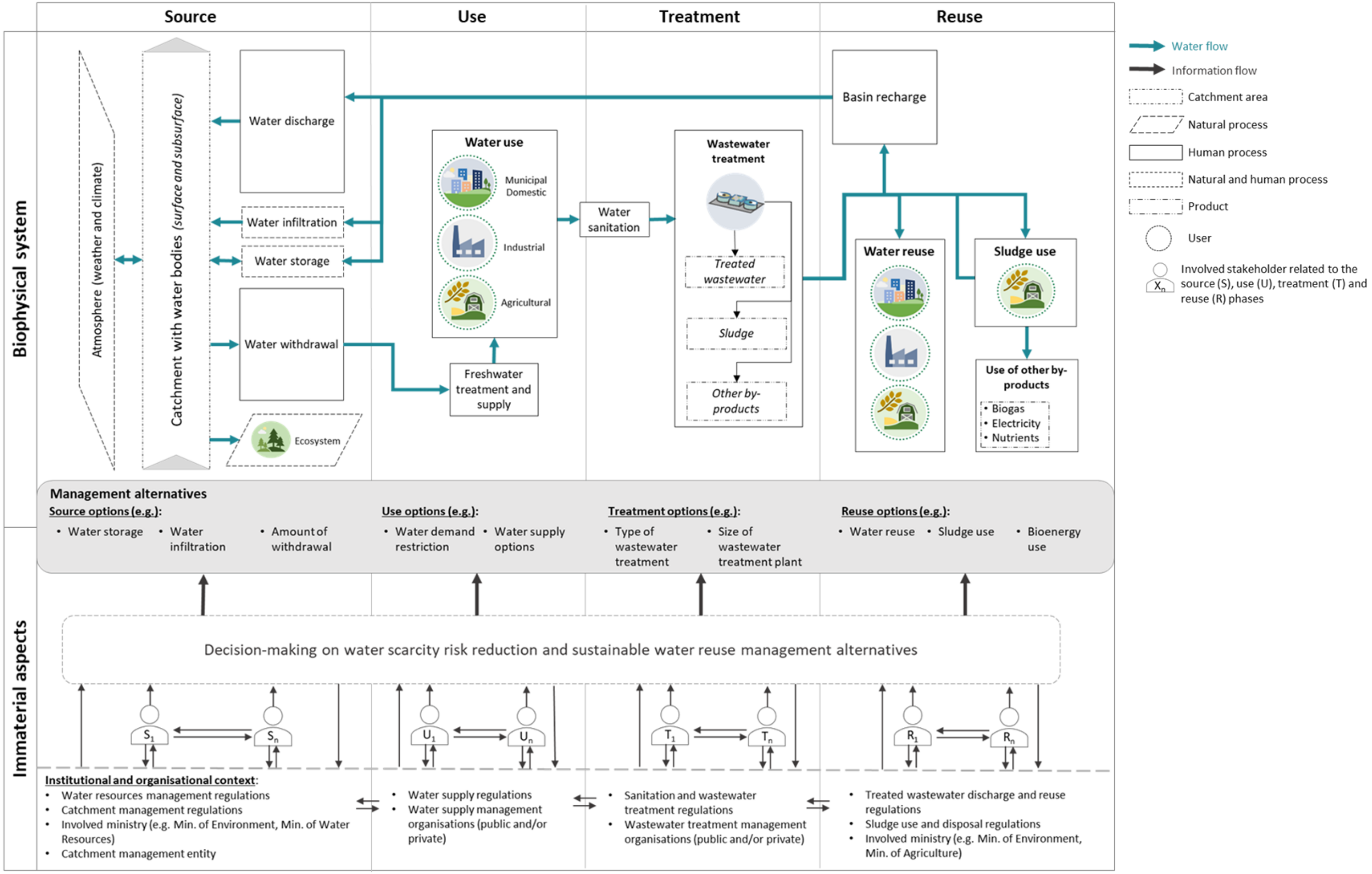

Figure 2.5: Representation of the 'water scarcity – water reuse' situation as a simplified CHANS. The upper section presents the relevant elements and water flows related to the natural and human biophysical aspects. The lower section includes the immaterial aspects of the human sub-system related to water management.

2.3.2 Identifying and defining key concepts

The literature review provides an overview of the various, in many cases converging, understandings of the concepts relevant for the framework with the intention of creating a consistent basis. This is relevant because the 'water scarcity – water reuse' situation transcends to an interdisciplinary or even transdisciplinary realm, as already visible from the different sources of concept definitions.

2.3.2.1 Water scarcity

Water management can be split into three main aspects: quantity, quality and accessibility of water resources (Schulte and Morrison 2014). Issues associated with the quantity of water resources often refer to the terms 'scarcity' (as in "lack of") and 'stress' (see Table 2.1). The latter is usually indicated as a less severe condition than scarcity (e.g., Falkenmark et al., 1989). In contrast, Schulte and Morrison (2014) differentiate between both terms, where 'water scarcity' relates only to the availability of water (in quantitative terms) and 'water stress' involves any issue pertaining either quantity (availability), quality or accessibility of/to water resources. Nevertheless, all of the definitions of 'scarcity' and 'stress' allude to the inability of meeting the needs or demand of the human population. Thus, the discussion must not only contemplate natural hydrological aspects but recognise the intrinsic human component that shapes this term, i.e. there is no scarcity if no human requirement has to be met.

There seems to be a prevailing subjectivity in the use of terms that can lead to a general ambiguity — for instance, the relation between the terms 'availability' and 'scarcity'. Although 'availability' is often referred to as the quantity of water resources (e.g., Hoekstra, 2000; Schulte and Morrison, 2014), it can also refer to a situation that does not only comprise the quantity of water but also its quality and accessibility; especially when the quality of the water resources is not appropriate or they are not accessible, then they are ultimately not available for human use. Thus, when addressing scarcity as focused on quantitative availability, it is more appropriate to maintain the concrete use of 'quantity' instead of 'availability'. Combining this to the view presented by Schulte and Morrison (2014), the term water stress can be applied as a degree of the net availability of water for human use, considering quantity, quality and accessibility, rather than as general term for water scarcity only.

The use of the term 'water scarcity' is already discussed by Hoekstra (2000), highlighting that it can respond to a "*supply problem*", a "*demand problem*" or an economic perspective of water. Later, Gain and Giupponi (2015) emphasised two primary measurements of water scarcity: supply-driven, which is the available quantity of water for human use with respect to renewable freshwater resources; and demand-driven, referring to how much water is demanded with respect to the available quantity. In the first case, the focus is set on the water available for withdrawal, whereas in the second case, the focus point is the human demand for water. Either way and according to a general definition, water scarcity refers to an amount of water for human use. It is worth mentioning, that there is discussion about considering environmental or ecosystem water requirements to determine the water resources available for human use (Oki and Kanae 2006; Schulte and Morrison 2014; Schneider and Avellan 2019), directly relating to their relevance in defining water scarcity.

Table 2.1: Selected water scarcity and water stress definitions

Term	Definition	Source	Comment
Water Scarcity	*"The concept 'drought' is being used rather haphazardly, more or less equivalent to water scarcity. When lack-of-precipitation phenomena are 'filtered' through an overpopulated/overexploited area, the results are the desiccation of the landscape and the risk of collapse of the socio-economic system. In principle, we recognise 4 different types of water scarcity"*: *(A) Aridity; (B) Intermittent droughts; (C) Landscape desiccation; (D) Water stress.*	Falkenmark et al. (1989, 259)	Includes 'water scarcity' within a broader definition of 'water stress'
	"Water scarcity concerns the quantity of resource available and the quality of the water because degraded water resources become unavailable for more stringent requirements".	Pereira et al. (2002, 176)	Does not refer to 'water stress'
	"A system suffering from water scarcity is one in which there is insufficient water available to meet demand at any specific time".	WRG (2013, 10)	Does not refer to 'water stress'
	"Water scarcity refers to the volumetric abundance, or lack thereof, of freshwater resources. 'Scarcity' is human-driven; it is a function of the volume of human water consumption relative to the volume of water resources in a given area".	Schulte and Morrison (2014, 4)	Clearly differentiate between the meaning of 'water scarcity' and 'water stress'.
	"Water scarcity is defined as the point in which the impact of all users undermines the supply or the quality of water, under the established institutional arrangements, to the point of not satisfying the demand of all sectors including the environment".	Ballestero et al. (2015, 11)	Use interchangeably 'water scarcity' and 'water stress'
	"Physical water scarcity occurs when there is not enough water to meet all demands (including the environment)".	Vanham et al. (2018, 219)	'Water stress' is used to measure the level of 'water scarcity'
	"An imbalance between supply and demand of freshwater in a specified domain (country, region, catchment, river basin, etc.) as a result of a high rate of demand compared with available supply, under prevailing institutional arrangements (including price) and infrastructural conditions. Its symptoms are: unsatisfied demand, tensions between users, competition for water, over-extraction of groundwater and insufficient flows to the natural environment. Artificial or constructed water scarcity refers to the situation resulting from over-development of hydraulic infrastructure relative to available supply, leading to a situation of increasing water shortage".	FAO (n.d.)	Does not refer to 'water stress' but differentiate between "chronic" and "absolute water scarcity" referencing Falkenmark et al. (1989)
Water Stress	*"Water stress indicates the intensity of pressure put on water resources and aquatic ecosystems by external drivers of change. Generally speaking, the larger volume of water withdrawn, used and discharged back into a river, the more it is degraded and/or depleted, and the higher the water stress".*	Alcamo et al. (2007, 250)	Does not refer to 'water scarcity' in detail
	"Water stress refers to the ability, or lack thereof, to meet human and ecological demand for freshwater. Compared to water scarcity, water stress is a more inclusive broader concept. It considers several physical aspects related to water resources, including water availability, water quality, and the accessibility of water […], which is often a function of the sufficiency of infrastructure and the affordability of water, among other things".	Schulte and Morrison (2014, 4)	'Water stress' is a broader term that involves 'water scarcity'. Do not specify the involvement of degrees of 'water scarcity' measured as 'water stress' levels.
	"Water stress occurs when the demand for water exceeds the available amount during a certain period or when poor quality restricts its use. Water stress causes deterioration of freshwater resources in terms of quantity (aquifer over-exploitation, dry rivers, etc.) and quality (eutrophication, organic matter pollution, saline intrusion, etc.)".	EEA (n.d.)	Does not refer to 'water scarcity'

Since this work follows the line of a CHANS with natural and human biophysical and immaterial aspects, the terms 'water withdrawal' and 'water demand' are differentiated. Water scarcity involves the quantity of natural water resources available for withdrawal, a biophysical human aspect to fulfil a specific water demand, a human immaterial aspect. Hence, 'water withdrawal' is the actual amount physically extracted (human biophysical aspect – supply driven), whereas 'water demand' here refers to the amount of water required by society, which may or not be met (involving immaterial aspects as well – demand driven). In general, there is a direct relationship between both of these terms which is why water withdrawal is used to estimate water demand (Vörösmarty et al. 2000; Rosegrant and Cai 2002; Oki and Kanae 2006). Table 2.2 presents the definitions used for the integrated RSA Framework.

Table 2.2: Definitions of water scarcity and water stress applied for the integrated RSA Framework

Term	Definition	Source
Water scarcity	Lack of *"volumetric abundance […] of freshwater resources"* to meet human demand.	Schulte and Morrison (2014; modified)
Water stress	*"[…] ability, or lack thereof, to meet human and ecological demand for freshwater […] It considers several physical aspects related to water resources, including water"* quantity, *"water quality, and the accessibility of water […]".*	Schulte and Morrison (2014; modified)
Water availability	Level of quantity, quality and accessibility of/to water resources to meet human demand. The less water availability there is, the higher is the level of water stress.	Derived from Schulte and Morrison (2014)

2.3.2.2 Water reuse

The interchangeable use of several terms, such as 'water recycling', 'treated wastewater reuse', 'water reuse' and 'water reclamation', generates confusion (Ricart and Rico 2019). Because of its widespread application, this work refers mainly to the terms 'water reuse' and 'water reclamation'.

The International Organisation for Standardisation (ISO) defines 'water reuse' as the "*use of treated wastewater for beneficial use*", allowing to employ it as a synonym of 'water reclamation' (ISO 16075-1, 2015). Some organisations like the German Association for Water, Wastewater and Waste (DWA) make use of this definition. However, other authors and regulations highlight differences between both terms. In those cases, water reclamation refers to a particular instance of water reuse that involves additional rigorous treatment for more restricted uses (Asano et al. 2007; Ansari et al. 2018; European Commission 2018; Ricart and Rico 2019). The "Proposal for a regulation on minimum requirements for water reuse" of the European Commission (2018) indicates that water reclamation involves the treatment of urban wastewater in a reclamation treatment plant, following specific requirements. Therefore, water reclamation refers to a type of water reuse that allows providing water that meets particular quality characteristics.

This work recognises the difference in water reuse and reclamation as well as the fact that water reclamation is a type of water reuse (see Table 2.3). However, for practical reasons and because this framework does not strictly define the use of the treated wastewater, the choice is to refer to the general term: water reuse.

Table 2.3: Working definitions for water reuse and reclamation

Term	Definition	Source
Water reuse	"*Use of treated wastewater for a beneficial use*".	ISO 16075-1 2015
Water reclamation	A rigorous treatment of wastewater in a water reclamation treatment plant to make it directly "*reusable with definable treatment reliability and meeting appropriate water quality criteria*".	Based on Asano et al. (2007, 5), European Commission (2018, 20) and Ricart and Rico (2019, 430)

2.3.2.3 Risk and risk assessment

According to the United Nations Office for Disaster Risk Reduction (UNDRR; formerly UNISDR), disaster risk is "*the potential loss of life, injury, or destroyed or damaged assets which could occur to a system, society or a community in a specific period of time, determined probabilistically as a function of hazard, exposure, vulnerability and capacity*" (UNDRR, n.d.). The operationalisation of risk considers it to be a function of hazard, exposure and vulnerability of the studied system (e.g., Blanco-Vogt and Schanze 2014; Garrick and Hall 2014; Rubert and Beetlestone 2014; Sayers et al. 2016). Table 2.4 shows the respective working definitions used in this research.

Risk assessments (RA) provide decision-makers with information related to the probable responses when exposed to a hazard (Zio 2018) to explore means of risk reduction. There are well-developed and structured assessment frameworks to assess risk, guiding the identification, analysis and evaluation of hazards and their impacts, and resulting risk (Zio 2018). These assessments involve two main tasks: (i) risk analysis (sources, pathways, receptors and consequences); and (ii) risk evaluation (Schanze 2009).

Table 2.4: Definitions on risk for the integrated RSA Framework

Concept	Definition	Source
Hazard	The probability of occurrence and features of an event (natural or human-made) with the potential to result in harm, as in "*loss of life, injury or other health impacts, property damage, social and economic disruption or environmental degradation*".	Based on the definitions of Schanze (2006) and UNDRR (n.d.), respectively.
Exposure	"*The people, livelihoods habitats, species, infrastructure or economic, social, or cultural assets*" that are "*located in hazard-prone areas*".	Based on the definitions of Sayers et al. (2016, 22) and UNDRR (n.d.), respectively.
Vulnerability	"*The propensity or predisposition of a given receptor (or group of receptors) to be adversely affected*" considering its physical, social, economic, ecological and institutional "*value(s) or functions, susceptibility and coping capacity*".	Based on the definitions of Sayers et al. (2016, 24) and Schanze (2016, 2), respectively.
Risk	"*Probability of (negative) consequences or interference of hazard and vulnerability depending on exposure*".	Schanze (2016, 2)

2.3.2.4 Sustainability and sustainability assessment

The meaning of sustainability and sustainable development originated from the intention of reconciling human development and environment to improve human life quality (Marchese et al. 2018). The social, economic and environmental dimensions (otherwise known as the triple bottom line) help to understand and operationalise sustainable development acting as the three pillars of sustainability (Waas et al. 2011). Other dimensions such as the institutional dimension, related to democracy and governance (e.g., Waas et al. 2011; Toumi et al. 2017), and the cultural dimension (e.g., Balkema et al. 2002) appear as the fourth pillar in some cases. However, the three main pillars maintain their fundamental status in sustainability indistinctly of the approach. There are different definitions associated with these pillars, but they tend to point towards the same direction (e.g., Balkema et al. 2002; Waas et al. 2011). Table 2.5 shows the definitions used for the integrated RSA Framework.

Unlike risk, even with a set of defined dimensions, the challenge in operationalising sustainable development is handling it since the definitions outline "*a concept rather than giving [a] rigid rule*" (Balkema et al., 2002, p. 154). This can be an opportunity that allows flexibility to adapt to the different needs and circumstances, but it implies a more significant challenge for its practical implementation (Waas et al. 2011).

Table 2.5: Definitions on sustainability for the integrated RSA Framework

Concept	Definition	Source
Sustainable development (SD)	"*[...] to ensure that it [development] meets the needs of the present without compromising the ability of the future generations to meet their own needs*".	UN (1987, 24)
Sustainability	A "*continuous search for a delicate equilibrium in a dynamic setting*" "*striving for the maintenance of economic well-being, protection of the environment and prudent use of natural resources, and equitable social progress which recognises the just needs of all individuals, communities, and the environment*".	Combination of the definitions of Muga and Mihelcic (2008, 438) and Waas et al. (2011, 1646), respectively
Social	Securing people's socio-cultural needs by achieving an "*equal distribution of welfare, access to natural resources and equal opportunities between people (gender, social groups, etc.)*".	(*)
Economic	Increasing "*long-term well-being*" through "*optimal allocation and distribution resources*" "*to satisfy essential needs*" (e.g., water, food, energy, sanitation, social security).	(*)
Environmental	Protecting, conserving or enhancing the "*ability of the functions of the environment to sustain the human ways of life*" "*within the Earth's environmental limits*".	(*)

(*) Based on the definitions of Balkema et al. (2002, 154) and Waas et al. (2011, 1651)

Despite the associated challenges of the analysis and evaluation of sustainable development, a broad term defining this endeavour is 'sustainability assessment' (SA). SA is the most commonly used term amongst many others, e.g., 'sustainability appraisal', 'integrated assessment', 'integrated SA', 'sustainability impact assessment', 'triple-bottom-line assessment', '3-E integrated assessment' (environment, economy, equity) and 'extended integrated assessment' (Pope et al.

2004; Hacking and Guthrie 2008; Pope et al. 2017). There are different definitions and understandings of SA (e.g., Hacking and Guthrie, 2008; Sala et al., 2015; Pope et al., 2017). The one presented by Hacking and Guthrie (2008, 73) and used in this framework is broad enough for various decision-making situations (e.g., policies, programmes, plans, projects, etc. involving individual or collective issues): a "*means of directing planning and decision-making towards sustainable development*".

2.3.2.5 Decision-making

Although decision theory provides different views, it is well established that decision-making commonly aims at maximising the gains, benefits or achievement of defined interests (Edwards 1954; Tversky and Kahneman 1986). This also means minimising the maximum losses or maximising the minimal gain (Edwards 1954). Whether it is including phases of framing, editing and evaluation (Tversky and Kahneman 1986), or considering simplification tasks that involve decomposition, editing or heuristics (Redlawsk and Lau 2013); there are common aspects in behavioural decision theory that lead to a final decision or choice (output): (i) identification of the interest, goal, or aim; (ii) framing and decomposing, and (iii) an evaluation (see Figure 2.6). The framing and decomposing stage delineates the boundary of the problem and breaks it into elements that are easier to evaluate. In doing so, the interest or aim might change, and the process restarts (feedback). If that is not the case, the evaluation phase judges the components according to defined criteria, targets or thresholds (depending on the aim). Finally, a rational choice corresponds to the best-evaluated alternative that mostly allows fulfilling the interest or aim (Tversky and Kahneman 1986; Redlawsk and Lau 2013). All three steps or phases are embedded in a specific context and rely on constant input and output of data and information. Thus, decision-making can be categorised as a sequence of steps with cyclic feedbacks that leads to a decision.

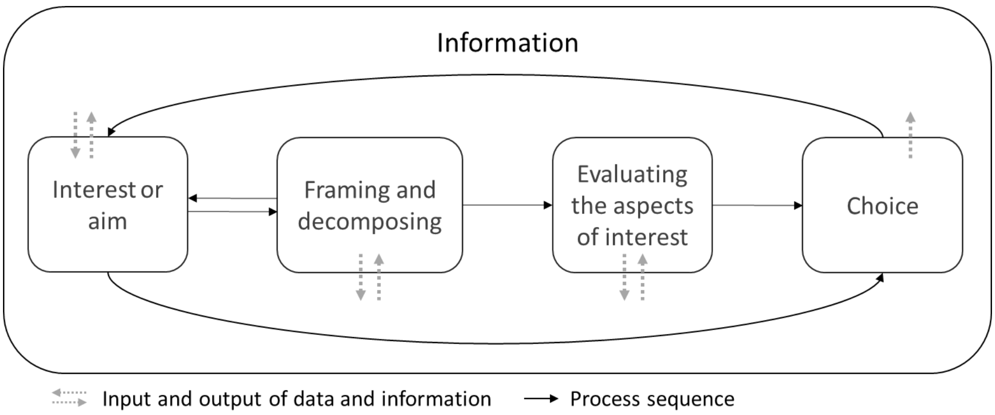

Figure 2.6: Decision-making as the sequence of steps to make a choice considering data and information.

2.3.3 Construction of the integrated RSA Framework

This third step is dedicated to the construction of the framework. First, it comprises the incremental interrelation of the key concepts defined in the previous section. Second, the integrated RSA Framework itself is compiled.

2.3.3.1 Interrelating the key concepts

Water scarcity from a risk perspective

Water scarcity is fundamentally associated with threatening natural conditions and adverse social, economic and environmental consequences such as the lack of water for basic household needs (e.g., washing and cooking) (WWAP 2018). Thus, it involves an intrinsic risk. As a risk, it can be expressed as a probability function of negative consequences due to the change of natural or human aspects. This function describes the human water demand (human immaterial aspect) being exposed to the hazard of a decrease in water quantities available for human use (natural and human biophysical aspects). These components shape the interpretation of the risk dimensions as shown in Figure 2.7.

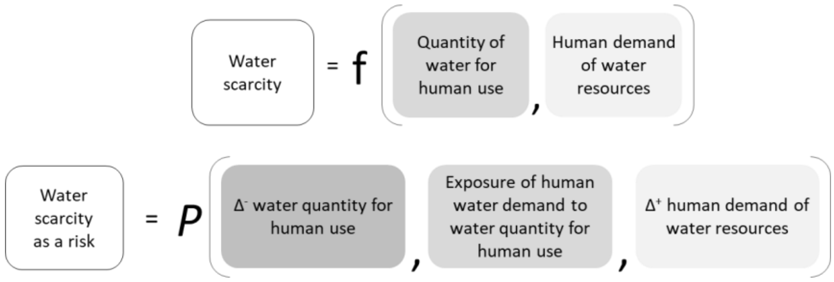

Figure 2.7: Water scarcity and water scarcity as a risk presented as functions. Based on the notation proposed by Sayers et al. (2016)

At a glance, the 'hazard' seems to be related to reduced quantities of water resources available for human use. A reduction of water resources does not directly imply adverse effects, but it can potentially "*result in harm*" which fits the definition of hazard. There are different reasons for a decrease (negative delta) in the quantity of water resources, which relate to the natural and human biophysical aspects and can be distinguished as source and pathways according to the source-pathway-receptor concept (e.g., Sayers et al. 2016). The decrease can be triggered by drivers of change such as climate change, upstream land-use change or water withdrawal (e.g., Vörösmarty et al. 2000). This understanding connects the hazard at the 'source' and 'use' categories of the proposed system's representation of the 'water scarcity – water reuse' situation and directly points to the catchment water bodies considering climatological and hydrological processes as well as human water uses.

'Exposure' relates to the "*hazard-prone areas*" and all the elements (receptors) that are within that area. A decrease in the quantity of water resources (hazard) fundamentally relates to elements (e.g., municipal or domestic, industrial, agricultural) with a human demand for water resources. What constitutes the exact boundaries of an exposed area is circumstantial and usually involves contextual (e.g., water infrastructure), spatial (e.g., river valley) and temporal features (e.g., under future boundary conditions due to climatic change) (e.g., DGA, n.d.).

Table 2.6: Water scarcity as a risk: definition in terms of the risk dimensions

Dimension	Interpretation for water scarcity (*)
Hazard	Probability of a decrease in the quantity of water resources for human uses.
Exposure	The processual spatial and temporal interrelation of quantity of water resources for human uses and human water demand that results in affected people, livelihoods, habitats, species, infrastructure or economic, social or cultural assets.
Vulnerability	Human demand of water resources and its physical, social, economic and ecological values or functions, susceptibility and coping capacity.
Risk	Probability of insufficient quantity of water resources for human uses to fulfil the human water demand (negative balance) depending on processual spatial and temporal interrelation of this quantity and demand.

(*) Based on the definitions in Table 2.4

Defining the exposed area allows to specify the system's representation of the 'water scarcity – water reuse' situation, by identifying the involved elements, e.g., the exposed area entails intense agricultural activities which determine the demand for water resources and diminish the role of drinking water treatment processes. This allows characterising the system according to the local context.

'Vulnerability' refers to the human demand for water resources that is susceptible to a decrease in water resources. In addition to human biophysical aspects, such as water use and respective technologies, it comprises social, economic and environmental values and functions (Blanco-Vogt and Schanze 2014). The demand may underlie a spatial pattern and temporal variability. Moreover, it can change in the long run due to e.g., demographic development, urbanisation, and intensification of agricultural use. For example, communities located in areas arid or semi-arid regions can be highly vulnerable to an increase in water demand (e.g., in a hot and dry season) (FAO 2017; Voulvoulis 2018). The coping capacity can be manifold with measures ranging from water harvesting in rainy seasons to emergency water supply through road tankers.

Water scarcity as a 'risk' is the likelihood of not fulfilling the human water demand due to a decrease in the quantity of water resources for human use. It may result from either a decrease of the freshwater resources due to climatological-hydrological processes or the increase of human demand on the one hand, or simultaneous occurrence of both on the other hand. In this case, a risk assessment consists of a combined analysis and evaluation of the hazard, as the decrease of the quantity of water resources, the vulnerability of human water demand, maybe undergoing seasonal or long-term increase, and depending on exposure. The likelihood of its occurrence needs to be calculated as probability and, if possible, additionally with its uncertainty.

The representation of the 'water scarcity – water reuse' situation as a system can facilitate the analysis of the risk by underlining exposed and highly vulnerable elements of the system. For instance, there is a fast-growing city with increasing water demand, which sets the focus on the municipal element of the system, as well as on all the related aspects for water supply (water withdrawals, drinking water treatment). A system's visualisation can serve as a mental map supporting the analysis of the conceptual components of risk, facilitating the comprehension and implications of a water scarcity situation.

Water reuse from a sustainability perspective

This subsection focuses on the characteristics of water reuse measures to be sustainable, emphasising on quantity of water supply (see Table 2.7). Potential water quality issues are acknowledged and thus quality risks for the sustainability of water reuse are presented in the next subsection.

From a societal perspective, a sustainable water reuse measure can secure social needs by providing ready-to-use, contaminant-free water resources and hence support social well-being. Challenging social aspects such as perception and acceptance can be addressed through capacity development, empowerment and active participation of the community to allocate the reuse measures where they are most needed and socially accepted (Baggett et al. 2006; Rice et al. 2016; Khanpae et al. 2020). Another challenge relies on the coordination of the water supply and sanitation sectors and the participation of the involved stakeholders (FAO 2017; Ricart and Rico 2019).

From an economically sustainable perspective, a (re-)valorisation of water resources and the possible by-products (e.g., energy, nutrients) resulting from their treatment can foster long-term resource-efficiency under careful considerations of financial and scale (treatment plant size) aspects (Asano et al. 2007; Yang and Abbaspour 2007). The challenge is to provide an interesting and feasible business model that compensates the expenses of the needed treatment processes, e.g., circular economy perspective (IWA 2016; Voulvoulis 2018).

The contribution of water reuse to environmental sustainability relies on reducing the demand for freshwater resources by providing further uses for already "used" water. This can reduce the depletion of water resources (WWAP 2017; Libutti et al. 2018) and hence support the protection, conservation and enhancement of the ability of the environment to sustain human needs. Furthermore, treatment and reuse may advance overall purification and release water with proper quality for discharge in water bodies avoiding further contamination. Still, there are some challenges in this dimension, such as greenhouse gas emissions from energy demand (Hafeez et al. 2014) as well as environmental risks (see next subsection).

Table 2.7: Water reuse as a sustainable measure: the perspective of the sustainability dimensions

Dimension	Interpretation for water reuse (*)
Social	Securing people's social-cultural demand of water resources by providing ready-to-use and contaminant-free treated wastewater.
Economic	Ensuring economic feasibility of the water reuse measure through optimal allocation and distribution of resources to increase long-term resource-efficiency.
Environmental	Protecting, conserving or enhancing the ability of the environment to provide water resources through efficient water reuse management and adequate protection from pollution.

(*) Based on the definitions in Table 2.5

Water scarcity and other risks for sustainable water reuse measures

There are different aspects that pose risks to the sustainability of a water reuse measure, i.e. for the fulfilment of the definitions presented in Table 2.7. On the one hand, the risk of water scarcity affects the feasibility of the implementation of a water reuse measure, because if the water scarcity is severe there is the possibility of expecting not enough wastewater quantity for a reuse measure (e.g., Beveridge et al. 2017; Tran et al. 2017). In the case of a less severe water scarcity, there is still the risk of concentrating pollutants in the wastewater which challenges the performance of the wastewater treatment systems as well as increasing the associated costs (Tran et al. 2017). These issues are of relevance for the integrated RSA Framework and may challenge water reuse measures as a sustainable means of reducing the risk of water scarcity.

On the other hand, there are social and environmental risks associated to water reuse itself, mainly related to the quality of the treated wastewater. In the first case, water reuse can pose a risk to human health due to contact and/or ingestion of hazardous components (e.g., heavy metals, pathogens) present in the treated wastewater (e.g., Toze, 2006; FAO, 2017; Ricart and Rico, 2019). Likewise, the existence of pollutants in the treated wastewater can also affect the environment, for instance, soil properties (e.g., increased salinity and heavy metal concentration) (e.g., Urbano et al., 2015; FAO, 2017; Khanpae et al., 2020). Therefore, it is common to find regulations and guidelines for safe water reuse, such as the "*health protection measures*" proposed by the WHO, ranging from the classification of crops to irrigation strategies (WHO 2006).

Other risks related to water supply, sanitation and treatment processes that should be considered are accidental leakage and cross-connection events (e.g., Oesterholt et al. 2007; Sercu et al. 2011). Likewise, the compliance of relevant financial and regulatory instruments is an important factor challenging water reuse measures (Avellán et al. 2019). All of these aspects, along with the mentioned health and environmental issues, should be considered when designing and implementing a water reuse measure (Avellán et al. 2019). This can be addressed by including the respective indicators for evaluation in the SA (e.g., Spiller 2016; Benavides et al. 2019) .

2.3.3.2 Integrated Risk and Sustainability Assessment (RSA) Framework

Specifying the key concepts and interrelating them for a 'water scarcity – water reuse' situation sets the basis for the integrated RSA Framework for decision support. This framework includes a risk assessment for water scarcity and a sustainability assessment for water reuse to support decisions regarding the implementation of water reuse as means of water scarcity risk reduction, focusing on water quantity. According to the definition of sustainability assessments given by Hacking and Guthrie (2008), the RSA Framework is defined as a procedure that aims to guide decision-making towards risk reduction and increased sustainability. In line with the tasks involved in assessments, the framework comprises an analysis phase and an evaluation phase.

To support decision-making in a 'water scarcity – water reuse' situation through an integrated assessment, risk and sustainability assessments need to be combined appropriately. The steps involved in decision-making serve as a basis to do so: (i) identification of the interest, goal, or aim; (ii) framing and decomposing, and (iii) an evaluation (see Figure 2.6). The interest or aim define the focus and type of assessment (e.g., quantitative, qualitative, level of stakeholder involvement). The framing and decomposing stage in decision-making relates to the analysis phase of the assessment, i.e. the identification of the different components or elements and interlinkages. Finally, the evaluation is explicitly present in the decision-making and assessment tasks, i.e. the judgement of the situation based on risk and sustainability criteria or thresholds. This work proposes that in the dynamic flow of information between the stages of decision-making, assessments provide a means of organising and processing information to understand and evaluate a 'water scarcity – water reuse' situation (see Figure 2.8). This way, the output of the integrated RSA Framework is the level of risk of water scarcity (or risk reduction) and the level of sustainability of water reuse measures. This information output can guide the decision-maker towards choosing the option or a set of management options that allow minimising the risk and maximising the sustainability in the assessed context.

The decision support framework is finalised by including the general structure of the integrated RSA in the representation of the initial decision-making situation (see Figure 2.3). Figure 2.8 presents an advanced conceptualisation of this situation, following the steps of the decision-making and including the risk and sustainability assessment (a detailed description of each step is given below). The proposed framework uses the sustainability dimensions to organise and process the information. Thus, the social, economic, and environmental aspects also hold true for the risk analysis and evaluation. By doing so, there is the possibility of decomposing the 'water scarcity – water reuse' situation into more focused fragments, allowing to address it from the perspectives of these three dimensions and through the lenses of risk and sustainability. This grants having a comprehensive view of the situation, considering, e.g., the social vulnerabilities to water scarcity, the social impacts of a water reuse measure and the relevant aspects to achieve social sustainability that include simultaneously a risk reduction (likewise for the other dimensions).

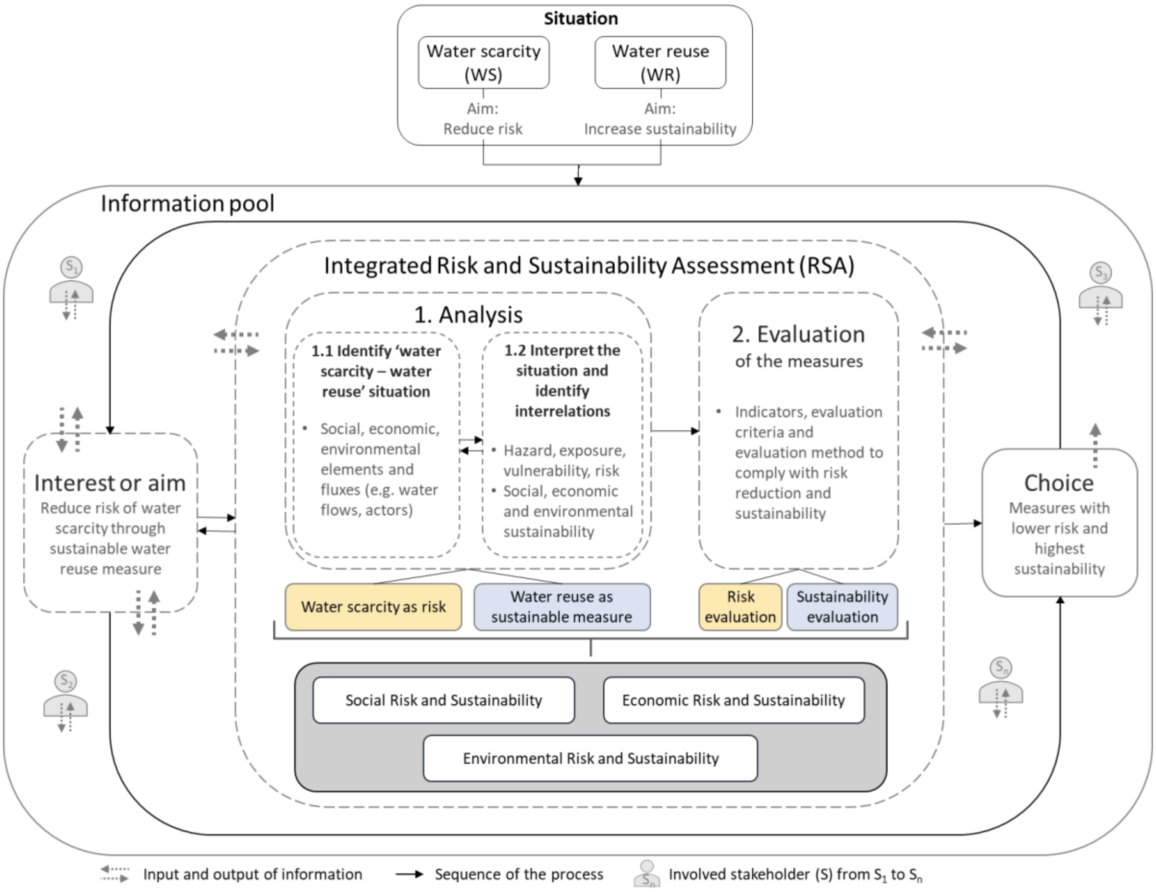

Figure 2.8: Integrated Risk and Sustainability Assessment (RSA) Framework for decision support.

Information pool

All the information used to define the aim and to perform the RSA Framework as well as the information generated in each of the decision-making steps flows from and into the general information pool. The input of different actors and stakeholders (e.g., public administration, private sector, civil society, NGOs, academia) enriches this information pool. The pool is heterogeneous and not entirely open as presented in the scheme, but rather exhibiting divisions that reflect the common information asymmetries. This is an issue that decision-makers need to be aware of and address because it directly influences the performance of this information-based assessment.

Interest or aim

Even though the specific interest or aim depends on the decision-makers, the principal intention underlying this framework is to reduce the risk of water scarcity through the implementation of sustainable water reuse measures. In other words, this means minimising risk and maximising sustainability. The assessment can be applied (i) *ex ante*, for decisions on different water scarcity scenarios and alternative water reuse measures to select the water reuse measures that should be implemented (similar to Opher et al. 2019) under a particular water scarcity situation; or (ii) *ex post*, for decisions on the performance of the current water reuse measure (similar to Benavides et al. 2019) under a given water scarcity situation for the identification of intervention points that can increase the sustainability and minimise the risk.

More specific interests or aims would include aspects that depend on the site-specific context, such as particular limitations and trade-offs, e.g., financial resources and time, or available capacity, among many others (Kurian et al. 2019). They could also point towards achieving synergistic results, e.g., coordination between the water supply and sanitation sectors (FAO 2017). These specific interests or aims do not undermine the main interest but can shape the assessment, highlighting aspects that need detailed analysis and determining evaluation criteria.

Analysis

The analysis phase provides an understanding of the 'water scarcity – water reuse' situation by identifying elements, processes, and fluxes, and interpreting their interrelations. It considers:

1. Identification of elements within the natural and human sub-systems: e.g., relevant water uses (e.g., in industry, agriculture), essential activities and processes (e.g., drinking water, sanitation and wastewater treatment processes), and actors (e.g., a list of stakeholders, main decision-makers, information holders). This could be supported by existing indicators related to the risk of water scarcity and the sustainability of water reuse.
2. Interpretation of the situation and identification of interrelations: natural and human aspects of the situation and the use of risk and sustainability dimensions for interpretation and interrelation of concepts.

The interpretation and representation of the situation as a CHANS (as shown in Figure 2.5) helps to visually place and connect the identified elements of the situation. Further categorisation can describe the nature of the interlinkages (e.g., as consumption -negative- or production -positive- values of water flows); drivers of water scarcity and water reuse (e.g., increase in water withdrawal); pressures (biophysical and societal); responses and impacts (social, economic and environmental.

Evaluation

The evaluation of the situation requires indicators and related criteria as targets or threshold values. Here, the indicators and target or threshold values could result from the analysis and refer to the level of risk for water scarcity and the level of sustainability for water reuse measures (e.g., Spiller 2016; Choi et al. 2017; Benavides et al. 2019). The analysis provides a systematic understanding of the 'water scarcity – water reuse' situation to select the indicators, whereof evaluation criteria may be derived from societal goals as e.g., set in legal regulations. The results of the analysis are evaluated based on the target or threshold values set in the respective step and lead to the combined level of risk and sustainability of the 'water scarcity – water reuse' situation. The choice requires a methodological structuring of the decision-making problem. This is typically done by the use of multi-criteria decision-making approaches such as multiple-attribute decision-making (e.g., AHP, TOPSIS) or multiple-objective decision-making approaches covering impact and equity analyses relevant for water security (Kalbar et al. 2012; Mardani et al. 2015, 2017; Nie et al. 2018). These approaches involve weighing and thresholds for the indicators. The current framework is not prescriptive of one evaluation method but rather allows using the method (e.g., multi-criteria evaluation methods) that is considered more suitable for each specific case.

It is important to highlight that at any stage of the assessment, given the newly generated information, there is the possibility of rethinking and changing the initial aim and restarting the procedure. However, the result of the analysis provides the data to evaluate different alternatives. This means that the evaluation is not a process that considers feedback like the analysis; instead, it is a snapshot of the analysed situation.

Choice

The final decision-making refers to alternatives for water scarcity risk reduction through sustainable water reuse. These alternatives can be portfolios of water reuse measures. They are analysed *ex ante* or *ex post* under water scarcity scenarios taking environmental and societal change into account. The chosen alternative is supposed to be the optimal choice for the initial interest or aim, i.e. minimising risk and maximising sustainability given context-specific restrictions. Another possible circumstance is an inconclusive one, where the final choice does not lead to a measure but rather to a change in the aim or focus and a restart of the process (feedback loop). This could be the case for a severe water scarcity that does not allow for a sustainable implementation of water reuse. In this case, the decision-maker should evaluate other alternatives to cope with water scarcity, e.g., desalination, inter-basin transfers.

2.3.3.3 Discussing the integrated RSA Framework

The proposed integrated RSA Framework focuses exclusively on water quantity issues consciously omitting water quality and access problems that may be present. It can be further expanded to a cascade process in which a first RSA assessment refers to the existing quantity of water resources to then further comprise risks associated to quality and finally to accessibility. This process is similar to the rationale proposed by the German Association for Water, Wastewater and Waste (DWA 2019) for the development of water reuse measures but integrating the risk and sustainability perspectives from the source until the discharge of water. However, it is suggested that indicators related to the water quality aspects of the water reuse measure are also included in the evaluation of the sustainability assessment, since they are relevant for a successful sustainable implementation. Accordingly, an enhancement of the framework would steer decision-makers' attention to these aspects with their particular relevance for water reuse.

Regarding the approach followed for the development of the framework and the final result (see section 2.2.2), there is compliance with the presented seven characteristics as follows: (i) the framework is constructed in a way, where each concept plays an integral role (i.e. risk and sustainability are used to interpret water scarcity and water reuse, respectively, and decision-making concepts together with risk and sustainability assessment support the structure of the assessment); all three steps of building the framework follow an (ii) interpretative approach to the 'water scarcity – water reuse' situation, (iii) providing an understanding instead of a theoretical explanation; (iv) the framework interprets intentions rather than knowledge of hard facts; (v) being indeterministic in nature; (vi) the development and construction followed a process of qualitative analysis; and (vii) the source of data, here mostly information, consists of many disciplinary concepts. These concepts will shape the practical implementation of the conceptual framework after its future operationalisation as methodology.

While this framework has not been tested yet, it offers a first approach of conceptual integration of risk and sustainability assessment for decision-making in 'water scarcity – water reuse' situations, in order to provide an aforethought structure that frames the empirical work (*ex ante* or *ex post*). The findings highlight the relevance of a consistent terminology for understanding the situation (what it comprises) and for the interrelation of the concepts. Further operationalisation of this framework is needed for a final testing in empirical cases.

Given the importance of information for the decision-making, such an assessment is ideally supported by involving the decision makers and the different stakeholders to foster an organised and transparent generation and exchange of information for water scarcity risk reduction (e.g.,, UNISDR 2005; Rubert and Beetlestone 2014) as well as acceptance of the water reuse measure (Pereira et al. 2002; Neto 2016; Ricart 2016; Usón et al. 2017; Zijp et al. 2017). This, in turn, can help in building trust and increase collaboration for water scarcity risk reduction via a implementation of sustainable water reuse measures (e.g., Pahl-Wostl et al. 2007; Dobbie et al. 2016).

2.4 Conclusions and outlook

This article provides four main contributions that can result relevant for water security in 'water scarcity – water reuse' situations from a risk and sustainability point of view: (1) a representation of the 'water scarcity – water reuse' situation as a CHANS; (2) a review on the concepts of 'water scarcity', 'water reuse', 'risk' and 'sustainability' with their assessments, and 'decision-making'; (3) an interpretation of water scarcity as a risk and water reuse as a sustainable alternative water source; and (4) the integrated RSA Framework for decision support as a first systematic conceptualisation of a simultaneous risk and sustainability assessment of water scarcity and water reuse. This research prepares for a methodological implementation of studies on water reuse in the context of water scarcity by portraying the possibility of combining efforts to address the 'water scarcity – water reuse' situation in a more comprehensive manner, analysing the situation as a system and interrelating relevant key concepts for decision support, and finally performing a joint evaluation based on risk and sustainability indicators and criteria.

The methodological implementation of the framework can mostly bear on established, but up to now independent methods for risk assessment on the one hand and sustainability assessment on the other hand. This is expected to foster exchange of information and collaboration among decision makers and stakeholders, highlighting how they are connected to and through the system. The final outcome for decision-making can be seen as a unified source of information with a comprehensive view of the situation.

The conceptual framework and its subsequent methodological implementation and empirical application will foster compliance with international policies on managing water scarcity. It mainly supports a joint risk and sustainability perspective as requested e.g., by the '2030 Agenda for Sustainable Development'. Accordingly, advances from this research are timely and call for further elaboration and testing under real-world conditions. Their empirical application is expected to support decision-making on various water management and governance levels regarding an integrated water scarcity risk reduction and sustainable development of water (re-)use as a means of resilience building.

Further research should primarily focus on the methodological implementation through consistent sets of indicators with target or threshold values and weights. Although this research focused on water quantity, it does not neglect water quality and accessibility. The latter two should play a prominent role in future research and their inclusion into this three-step procedure.

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Chapter 3 Methodological Aspects

This chapter corresponds to the published scientific article 2 (see sub-section 1.3.2). It addresses the methodological advancement of the conceptual framework. As the RSA Framework is not prescriptive on the evaluation methods, the focus of this chapter is the development of an analytical concept. This analytical concept follows the steps proposed by the conceptual framework: (1.2) identification of the WS-WR situation and (1.2) interpretation of the situation and identification of interrelations. As such, the core of this chapter is on:

- Identifying elements of the WS-WR situation from the perspective of a Coupled Human and Natural System (CHANS) using *endpoints*.
- Translating the CHANS *endpoints* into an information system via a Multi-Layer (ML) approach using generic *descriptors* and specific *indicators*.
- Identifying and characterising interlinkages between the *indicators* via a Lane-Based (LB) approach.

Translating the 'water scarcity – water reuse' situation into an information system for decision-making

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Abstract

One key challenge of water resources management is the identification and processing of the information necessary for decision-making. This article aims to provide avenues for translating a 'water scarcity–water reuse' (WS–WR) situation into an information system. It is dedicated to supporting an integrated assessment in decision-making with the final goal of optimising water scarcity risk reduction and water reuse sustainability. The approach combines the following two strands: (1) specific interpretation of systems thinking and (2) systemic characterisation and interlinkage of indicators. The result is an analytical concept that translates the WS–WR situation into an information system consisting of two structured components, a multi-layer (ML) and a lane-based (LB) approach. While the multi-layer approach supports the description of the elements of the biophysical and information systems such as endpoints and descriptors, respectively, the lane-based approach aids in understanding the importance of indicators within the entire system and their distribution across risk and sustainability realms. The findings from a generic exemplification of the analytical concept depict the feasibility of identifying system-based endpoints representing the WS–WR situation and their translation via descriptors to an interlinked indicator set to jointly assess water scarcity risk and sustainability of the water reuse measures. Therefore, this analytical concept supports addressing the water resources management information challenge via a structured representation of the system's complexity and the quantification and visualisation of interlinkages between the social, economic, and environmental dimensions of water scarcity risk and water reuse sustainability.

Keywords: water scarcity, water reuse, decision-making, systems thinking, indicator interlinkage, sustainability assessment.

3.1 Introduction

A challenging situation that decision-makers around the world face is to provide sufficient water in water-scarce areas. One solution is water reuse, i.e., the use of treated wastewater to supply water demands (FAO 2017; Voulvoulis 2018). Decision-makers here are tackling the issue of reducing the risk from decreasing or chronically lacking water quantities to meet human demand while providing sustainable solutions. The authors showed that an integrative way of thinking enables an inclusive decision in this context rather than sticking with two separated decisions: one on the reduction of risk and one on sustainable solutions (Müller et al. 2020). Accordingly, an integrated risk and sustainability assessment (RSA) framework has been proposed to analyse and evaluate data and information relevant from both spheres of knowledge resulting in one consolidated decision (ibid.). While this framework conceptually proves the possibility of integrating information from these two realms in a comprehensive manner, it still faces the issue of translating data into appropriate information. The latter particularly means how to choose the 'right' indicators for the assessment and hence the decision-making.

To carry out comprehensive risk and sustainability assessments for water resources management requires understanding complex interrelations between humans and the natural environment (Simonović 2009). Research in the fields of environmental and natural resource management (e.g., Speelman et al. 2007; Seiffert and Loch 2005) and specifically in water resource management (e.g., Simonović 2009; Davies and Simonovic 2011; Kotir et al. 2016), including risk- and sustainability-related studies, has highlighted the value of systems thinking in addressing complexity (e.g., Seiffert and Loch 2005; Di Baldassarre et al. 2013; Onat et al. 2017; Mai et al. 2020; Rubio-Martin et al. 2020). These approaches aim at reducing the complicatedness of real-world situations by interpreting them as a system, i.e., a sequence of interconnected elements functioning as a whole (Smithson et al. 2008). They support the representation of the situation and understanding of developments by (a) capturing the complexity and providing a big picture (Speelman et al. 2007; Rhoades et al. 2014), and (b) describing dynamics (Davidson and Venning 2011; Kotir et al. 2016; Mai et al. 2020). However, the interpretation (representation and understanding) as a system is strongly dependent on the involved scientists, experts, and actors, their field of knowledge, and their level and kind of expertise (Zamagni et al. 2013; Dalal-Clayton and Sadler 2014; Ricart C. 2016). Thus, the same situation may lead to different representations that drive indicator selection, where indicators critical for decision-making may be overlooked.

Therefore, bridging a systems view, ideally derived in an inter- and transdisciplinary setting (Bennich et al. 2020), with traditional risk and sustainability assessments may support a consistent selection of indicators for WS-WR situations. Insights on the types of indicators can show representation issues, e.g., of the dimensions of sustainability (e.g., Strezov et al. 2017; Oliveira Neto et al. 2018). Moreover, the analysis of the interlinkages between indicators may help identify which ones are critical to put in extra effort for data collection. The latter is supposed to help decision-makers focusing their resources on collecting representative and critical information about the situation, enabling them to see both the system as a whole and interlinkages that may not have been obvious.

This article aims to provide avenues for translating a 'water scarcity – water reuse' situation into an information system. It is dedicated to support an integrated RSA to optimise water scarcity risk reduction and water reuse sustainability, as described in Müller et al. (2020). The approach combines two strands: (1) specific means of systems thinking for system analysis and (2) systemic characterisation and interlinkage of indicators for the construction of an information system.

The reader can expect a conceptual and methodical article that presents the derivation of an analytical concept and its exemplification in a generic WS-WR situation. Section 3.2 briefly introduces the RSA Framework for WS-WR situations, as proposed by Müller et al. (2020). Section 3.3 describes the interpretation and translation of the situation (multi-layer approach), while section 3.4 addresses the characterisation and interlinkages of indicators (lane-based approach). Section 3.5 derives an overall analytical concept and an exemplification of the two approaches. Sections 3.6 and 3.7 refer to the discussion, and conclusions and outlook.

3.2 RSA Framework for a WS-WR situation

The current work builds on the conceptualisation of the RSA Framework for the integrated assessment of water scarcity risk and water reuse sustainability (Müller et al. 2020). Risk of water scarcity is understood as the probability of insufficient water quantity to fulfil human demand; where the hazard refers to a decrease in the quantity of water resources for human use, the exposure to the spatial and temporal interrelation of available resources and human demand, and the vulnerability to the human demand of water resources. Sustainability of water reuse refers, in said publication, to contribute fulfilling people's water demand, the ability of the environment to provide water and its protection from pollution via contaminant-free and ready-to-use treated wastewater, while ensuring economic feasibility and socially just allocation of resources. The framework with the aforementioned key concepts is used in the current article to guide an overall analytical concept for deriving, characterising, and interlinking indicators.

The systems view of the RSA Framework bears on a coupled human and natural system (CHANS). It differentiates between the biophysical system of the human-nature interrelations and the immaterial aspects of the human sub-system. This allows to portray material flows according to four water flow categories (source, use, treatment, and reuse) on the one hand, and the respective stakeholders with their interactions on the other (ibid.). In the current article, these two tiers form the basis for the differentiation between a biophysical system interpreting the water and water-related matter flows (section 3.3) and its translation in an information system with the characterisation of indicators and their interlinkages (section 3.4).

The information system supports the decision-making process with its continuous exchange of information. According to typical assessments, the RSA has been structured in a two-task procedure: analysis and evaluation (see Figure 3.1). In the analysis, the WS-WR situation is addressed by (1) identifying its relevant elements (step 1.1) and (2) interpreting the situation and interrelations between these elements (step 1.2). The analysis results provide the information necessary for evaluating the water scarcity risk and sustainability of the water reuse measures, bridging the aim and the evaluation within the decision-making process.

So far, the conceptual framework of Müller et al. (2020) could not provide further details on how to derive and organise the information in the analysis to support an appropriate evaluation. Thus, the current article elaborates on an explicit translation from the biophysical (step 1.1) to the information (step 1.2) system.

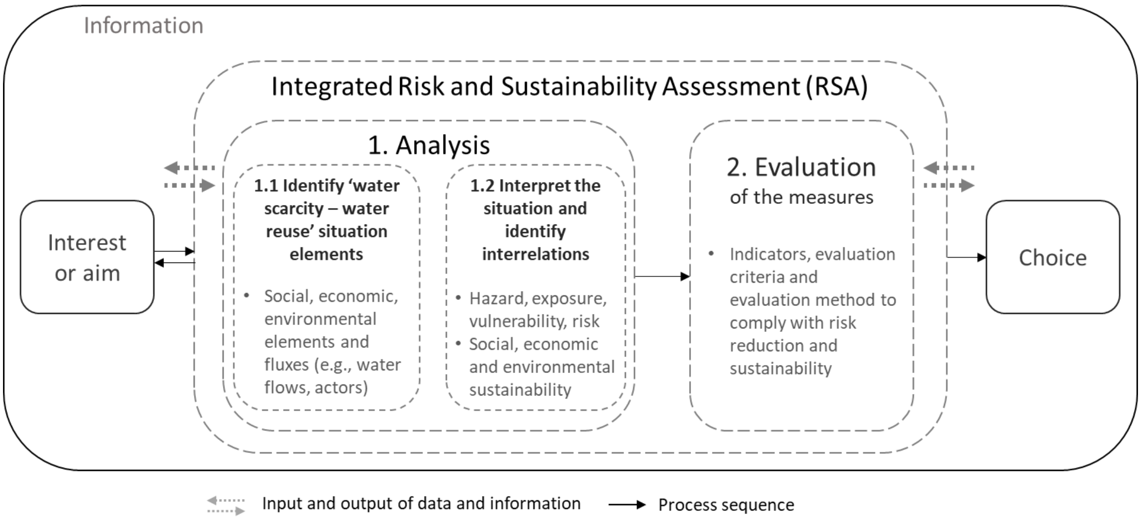

Figure 3.1: Integrated RSA comprising analysis and evaluation (Müller et al., 2020; modified)

3.3 Systems thinking in a WS-WR situation

On the one hand, systems thinking is generally recognised for addressing complexity (Seiffert and Loch 2005; Nguyen et al. 2015), especially when it comes to the structure, processes and interactions between human and nature for the design, planning and implementation of effective interventions (Alberti et al. 2011; Binder et al. 2013; Rhoades et al. 2014; Lawrence et al. 2020). Whether it is via social-ecological systems -SES- (e.g., Ostrom 2009), coupled human and natural systems -CHANS- (e.g., Liu et al. 2007), or human-environment systems -HES- (e.g., Scholz 2011), to mention a few, these approaches aim at improving the understanding of the situation's complexity. On the other hand, risk and sustainability assessments provide information on the situation to support decision-making. They do not aim to generate just any knowledge about the WS-WR situation but rather targeted knowledge by processing information, in this case, related to risk and sustainability, to evaluate the performance of the situation. Hence, how could the information of a system's interpretation be analysed to support the evaluation?

The following subsections describe which elements of the WS-WR situation should be identified for an interpretation as a biophysical system and its translation into an information system for decision-making.

3.3.1 Identifying elements of a WS-WR situation and its interpretation as a system

System dynamics approaches, e.g., Causal Loop Diagrams (CLD) and Stock-Flow Diagrams (SFD), focus on the interrelation of the system's elements as a means of representing real-world processes and analysing their behaviour over time (Sterman 2000; Winz et al. 2009; Schlüter et al. 2014). Causality interrelations between the elements allow defining balancing and reinforcing loops that characterise this behaviour (Lin et al. 2020). In water resources management, they have been used for identifying key elements (e.g., Simonović 2009; Z. Wu et al. 2020; Yazdandoost et al. 2020) with a focus on biophysical aspects (Kotir et al. 2016).

Thus, the first step in advancing the WS-WR situation's conceptualisation as a CHANS is to identify relevant biophysical elements of water scarcity and water reuse (step 1.1). These elements are named here *endpoints* – to differentiate them from the information system's elements – represent the state or performance of system processes as system variables. They need to be identified during a system analysis by researchers or expert practitioners and represent all water flow categories (source, use, treatment, and reuse). To do so, they can rely on a literature review for a top-down approach or engage in a variety of multi-, inter-, or transdisciplinary activities with different levels of participation for a bottom-up approach (e.g., focus groups, surveys, interviews) (e.g., de Vente et al. 2016; Horlings et al. 2020). Common elements that could be identified as endpoints are also found in SFDs. Endpoints of a system for a WS-WR situation include, e.g., available water resources, supplied water resources, available treated wastewater (more examples are found in section 3.5.2 and S2).

3.3.2 Translation of the CHANS into an information system

3.3.2.1 Descriptors for the translation of the system

Identifying the endpoints allows advancing towards a focused representation of the situation to understand the water-related processes. However, this representation remains at the biophysical level pushing towards the well-recognised challenge of interrelating the social, economic, and environmental aspects (Seiffert and Loch 2005; Simonović 2009) (step 1.2 of the analysis). This challenge seems to be enhanced if the relevant knowledge is widely distributed across disciplines (Sterman 2012; van Vuuren et al. 2016; Onat et al. 2017). Under the frame of an RSA, this mainly entails determining which social, economic, and environmental information related to the endpoints should be considered to support decision-making from the perspectives of risk and sustainability. This means translating the biophysical system perspective into an information system with the respective information elements. This information system refers here to a conceptualisation of organised information used by the RSA.

Therefore, the use of *descriptors* is proposed. They are understood as thematic conceptualisations of the meaning of the endpoints, taking (key) system functions or services into account accordingly (e.g., water resources available for human use – see example in section 3.5.2). In other words, descriptors connect the biophysical aspects with the immaterial aspects of the CHANS, in that, endpoints represent the biophysical elements of the CHANS and descriptors the guiding elements of the information system. They should be defined by researchers or expert practitioners depending on the interest and contextual characteristics of the case, aiming at answering, e.g., which information related to the biophysical endpoint is relevant from a social, economic, and environmental perspective in terms of risk and sustainability? The answer, and hence the descriptor, needs not yet to be as specific as an indicator to allow for an operationalisation with alternative indicators. As with the endpoints, this relies on top-down or bottom-up approaches such as literature or workshops and surveys, respectively.

3.3.2.2 Indicators to operationalise the descriptors

Provision of descriptive and partly not directly observable information in a classified manner is commonly made through *indicators* based on one or several *attributes* following specific algorithms (see section 3.4.4). In the case of the RSA, indicators generally employed for monitoring and evaluating the risk of water scarcity and sustainability of water reuse can be used to specify descriptors. Hence, indicators here are understood as information elements that operationalise the descriptors for the respective social, economic, and environmental dimensions. With the use of indicators, it is possible to compare elements that contribute to informing about the level of fulfilment of social, economic, and environmental requirements to reduce the risk and increase the sustainability.

3.3.2.3 The multi-layer approach: Translation of the CHANS into an information system

Overall, the translation into an information system relies on *endpoints* (CHANS biophysical elements) and *descriptors* and *indicators* (information elements), where one *endpoint* can have one or more *descriptors*, and one *descriptor* one or more *indicators* (see section 3.5.2). The traditional system dynamics visual representations (see section 3.1) do not fully represent this translation. However, multi-layer (ML) diagrams appear helpful as they use layers to portray sequential or hierarchical order, e.g., different scales (e.g., Alcamo 2003; Ewert et al. 2006), or different perspectives of the same basis layer (e.g., Basurko and Mesbahi 2014; Rikalovic and Cocic 2014). These representations have been widely used in social sciences (e.g., Bródka and Kazienko 2018; Di Gregorio et al. 2019), natural sciences (e.g., Rikalovic and Cocic 2014; Vermeulen et al. 2020), and particularly in engineering and computer sciences as "multi-layer networks" (e.g., Kivela et al. 2014; M. Wu et al. 2019).

Thus, for the RSA analysis task, an ML view helps conceptually capturing the translation into an information system, as shown in Figure 3.2. The layers can be understood as the interpretation of the biophysical system through the lenses of risk and sustainability and the views of social, economic, and environmental dimensions. This way, the ML approach provides a structure that differentiates the biophysical and the information perspectives while recognising their common origin. Moreover, it mirrors and translates the immaterial perspective by an indicator-based information system. This offers an alignment between the analysed WS-WR situation and the information for decision-making.

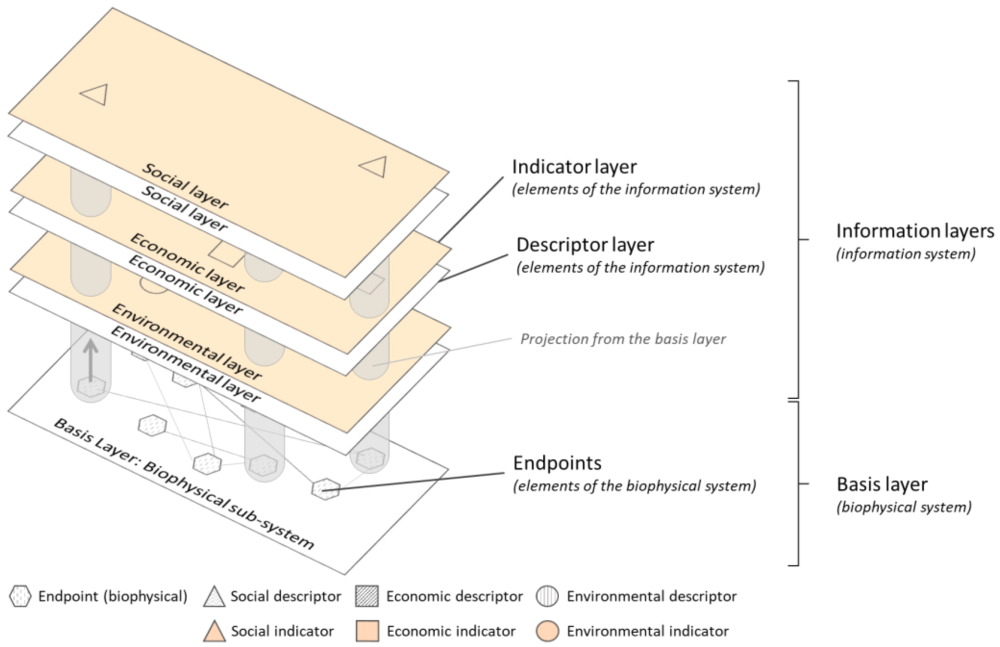

Figure 3.2: Representation of the ML approach

3.4 Characterisation and interlinkage of indicators

So far, relevant information elements (*indicators*) have been identified via the ML translation approach. However, knowledge about the indicators and their interlinkages across the risk and sustainability realms can support properly elaborating the information system as a whole. For the RSA, identified social, economic, and environmental indicators are characterised as risk-related (R-indicators), sustainability-related (S-indicators), and indicators that are used both in risk and sustainability assessments (RS-indicators), i.e., nine different types of indicators (see Table 3.1). Depending on the number of indicators identified, their distribution across dimensions may vary.

Interlinkages may exist within each dimension (intra-dimensional) and across them (inter-dimensional). In line with the indicators' characterisation mentioned above, four sorts of interlinkages are possible: (1) between two risk indicators (R-R), (2) between two sustainability indicators (S-S), (3) between risk and sustainability indicators (R-S), and (4) between two RS-indicators (RS-RS). As long as no directionality is specified, R-S is equal to S-R. For the case of interlinkages between RS-indicators with R-indicators or S-indicators, they should be counted as R-R and S-S interlinkages, accordingly.

Based on the different dimensions and types of indicators and interlinkages (see Table 3.1), it is possible to obtain information about (a) the general social, economic, or environmental performance when looking within each dimension, e.g., the social performance in terms of social risk of water scarcity and sustainability of water reuse (last column); (b) about the general water scarcity risk-related or water reuse sustainability-related performance when looking at inter-dimensional- and indicator-type-specific interlinkages, e.g., social, economic and environmental water scarcity risk-related performance (last row); and (c) about the entire system from both views including all types of indicators and interlinkages (bottom right corner). The latter suggests being the most challenging to process, given all types of indicators and interlinkages. Additionally, the mentioned information can be systematised in terms of (i) type and number of indicators, (ii) type and number of interlinkages, and (iii) indicator's connectivity (ratio of interlinkages per indicator).

Table 3.1: Information that can be derived from the information system.

	Indicator type			
Dimension	**Risk**	**Risk and sustainability**	**Sustainability**	**Intra-dimensional interlinkages**
Social	So-R indicators	So-RS indicators	So-S indicators	**Social performance**
Economic	Ec-R indicators	Ec-RS indicators	Ec-S indicators	**Economic performance**
Environmental	En-R indicators	En-RS indicators	En-S indicators	**Environmental performance**
Inter-dimensional interlinkages	**Risk-related performance**		**Sustainability-related performance**	**Risk- and sustainability-related social, economic, and environmental performance**

So: Social; Ec: Economic; En: Environmental; R: Risk; S: Sustainability, RS: Risk and Sustainability

3.4.1 Type and number of indicators

Following the ML approach, different types of indicators are identified for the respective descriptors and characterised as mentioned above. The distribution of those indicators across the sustainability dimensions and the water flow categories may vary, allowing the identification of data-intensive areas of the information system, i.e., where more data needs to be collected to provide the required information. On the one hand, variation within each dimension or layer can indicate data-intensive categories. On the other hand, when comparing all the layers, it is possible to analyse contrasting distributions and the most data-intensive dimension. The same can be observed for contrasts between risk- and sustainability-related indicators, e.g., a greater number of R- over S-indicators.

3.4.2 Type and number of interlinkages

Knowing the different types of interlinkages and their share can be a starting point towards deriving a correlation between, e.g., risk of water scarcity and sustainability of water reuse (at least in terms of the data required). Again, this analysis involves counting the number of intra-dimensional as well as inter-dimensional interlinkages. As long as there is no causality analysis between the indicators, it is impossible to define the direction of the influences (i.e., influenced or influencing). Table 3.2 shows in general terms the information that can be drawn from this analysis and its relevance for decision-making. This can be used to define the information system in terms of the interlinkage between the social, economic, and environmental dimensions, as well as between risk and sustainability (as introduced in Table 3.1).

Table 3.2: Information about type and number of interlinkages

Information derived from the information system	Relevance for decision-making
(1) Share of intra- and inter-dimensional interlinkages.	Indicate whether elements are likely to change due to intra-dimensional aspects, e.g., if social aspects are highly influenced by/influencing other social aspects, or if social, economic, environmental performance is highly interdependent.
(2) Share of the types of interlinkages at different levels.	Indicate how risk of water scarcity and sustainability of water reuse are correlated.
(3) Share of dimension-specific indicator’s involvement in intra- and inter-dimensional interlinkages and over the total number of interlinkages in the system.	Indicate the role of social, economic, and environmental indicators in the system's performance, as being decisive elements within their specific dimensions or to other dimensions.
(4) Share of dimension-specific indicator’s involvement in the different types of interlinkages.	Indicate the role of specific indicators within the risk perspective, the sustainability perspective, or the correlation between risk and sustainability.

3.4.3 Indicator connectivity

A rough calculation of the ratio between the number of indicators and the number of interlinkages leads to the indicators' connectivity. Connectivity can be calculated for (i) dimensions, e.g., number of social indicators over the number of interlinkages involving social indicators, (ii) risk and sustainability indicators, and (iii) the dimension-specific risk and sustainability indicators for a more detailed analysis, e.g., to find the most interlinked indicators. This defines the role that a specific type of indicator plays in the performance of the system, for each dimension and also for the risk and sustainability perspectives.

Based on the above, most interlinked indicators (MII) can be identified, i.e., indicators highly influenced by or influencing the system. Thus, if there are changes in the scores[2] of other indicators, it is highly likely that these MII also change; or if the score of an MII changes it is highly likely that the scores of multiple other indicators do too. This supports an optimised evaluation of the system, prioritising getting data for MIIs over others. It also supports identifying leverage points for reducing risk of water scarcity and increasing the sustainability of the water reuse measure. Again, depending on the aim of the study, it is possible to find the MII within each dimension, within the risk and sustainability perspectives, or both. For instance, if the MIIs belong to the social dimension and mainly corresponds to sustainability indicators, it calls for focusing on interventions that affect these indicators to increase sustainability. All of this information requests a structured and a compartmentalised approach for its visualisation and analysis.

3.4.4 Structuring via a lane-based approach

The three-dimensional layout of the ML approach might not be the best way of clearly visualising all the indicators and interlinkages. Here, it appears useful to refer to disciplines in business and industrial processes management, where different departments, functions, and activities have to be coordinated to provide a final product or service. This also means that different "dimensions" have to be portrayed together for a comprehensive view of the processes. A widely used diagram that portrays this is the Business Process Model and Notation (BPMN). While developed around 20 years ago (White 2004), it has been further advanced and ratified as a standard – ISO/IEC 19510:2013 (ISO 2013; OMG 2013). The main goal is to support the general understandability of processes (White 2004; OMG 2013), where activities are organised within different lanes (OMG 2013). These lanes allow a compartmentalised visualisation of the workflows i.e., interactions, between "internal roles (e.g., Manager, Associate), systems (e.g., an enterprise application), an internal department (e.g., shipping, finance)" (OMG 2013, 305). Similarly, the RSA analysis aims at providing decision-makers with an understandable representation of the interactions within the WS-WR situation. Therefore, it seems suitable to use a lane-based (LB) approach to represent the different indicator layers resulting from the ML approach (i.e., the dimensions of sustainability), as shown in Figure 3.3.

For the interlinkage analysis, in line with Entity-Relationship Diagrams (ERD) and Unified Modelling Language® (UML®), two standard approaches used to portray information systems (Chen 1976; OMG 2017), systems elements – entities in ERD and classes in UML® – can be further disaggregated into their fundamental components called *attributes*. Connections can be

[2] Here *score* is understood as the quantitative or qualitative measured value of an indicator, not referring to their relevance for the system.

established between the different elements based on the presence of the same attributes or the use of an attribute to derive another. For the WS-WR information system: *indicators* are portrayed in terms of their *attributes*, i.e., the most basic measurements used for calculating their score. Then interlinkages could be identified between *indicators* if two *indicators* have the same *attribute* or if there is a known correlation between them or their *attributes*. Thus, there is a hierarchical order between *endpoints*, *descriptors*, *indicators*, and *attributes*. Endpoints are described by social, economic, and environmental generic *descriptors*, which are operationalised through *indicators* that are further defined by *attributes*. The result is a network map that allows following the consequences of the changes in the scores of the *indicators* for a more detailed analysis of the performance of the system (see Figure 3.3). For instance, if the indicator score changes because of one *attribute*, then the score of other *indicators* linked to this *attribute* may also change, i.e., variations in one *indicator* might mean variations of other linked *indicators*.

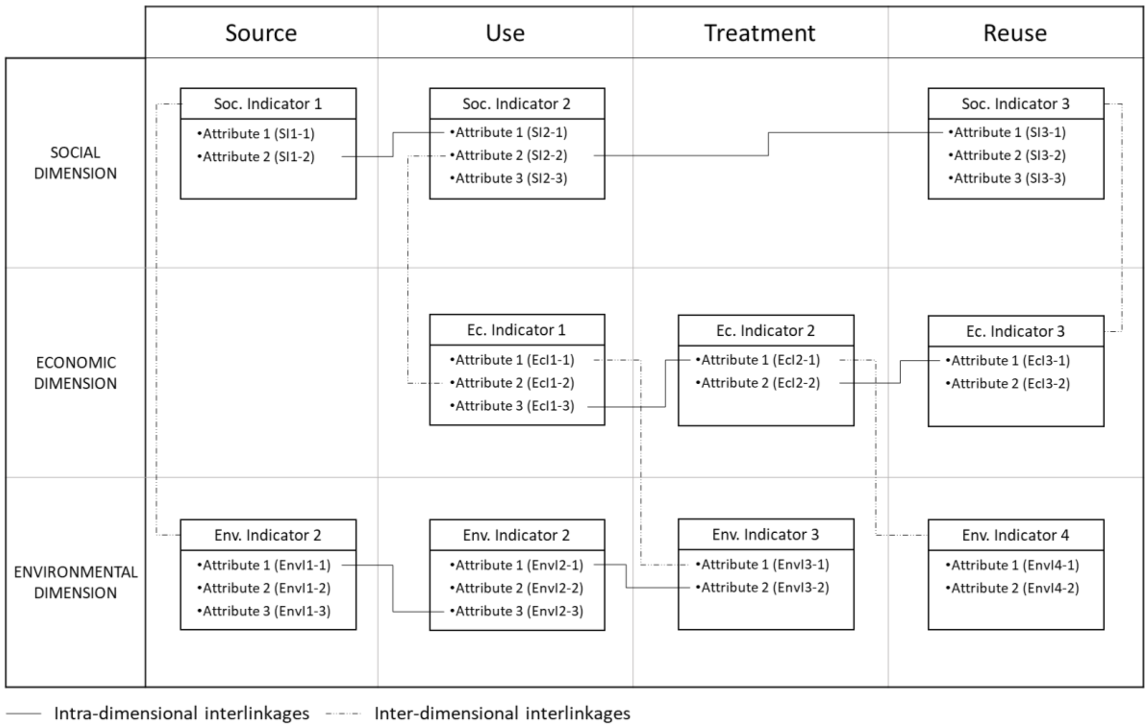

Figure 3.3: Lane-based approach for visualising the WS-WR information system. Schematic representation of an information system comprising three social indicators, three economic indicators, and four environmental indicators. Indicators are described by attributes, and interlinkages represent the use of the same attributes or a direct correlation between two indicators.

3.5 RSA analytical concept and exemplification

3.5.1 RSA analytical concept

Based on the described approaches, the analytical concept proposed here advances the RSA and the interpretation of a WS-WR situation as a CHANS by translating it into an information system via an ML approach involving the identification of relevant *endpoints* (step 1.1) and social, economic, and environmental *descriptors* and their respective *indicators* (step 1.2). It also proposes to analyse existing interlinkages by considering *attributes* and structure the visualisation of these interlinkages via an LB approach (step 1.2). Figure 3.4 shows a schematic view of the RSA containing the analytical concept, including the final LB grid as the starting point for the evaluation. Since the RSA is not prescriptive regarding the evaluation method, further specification exceeds the scope of this publication.

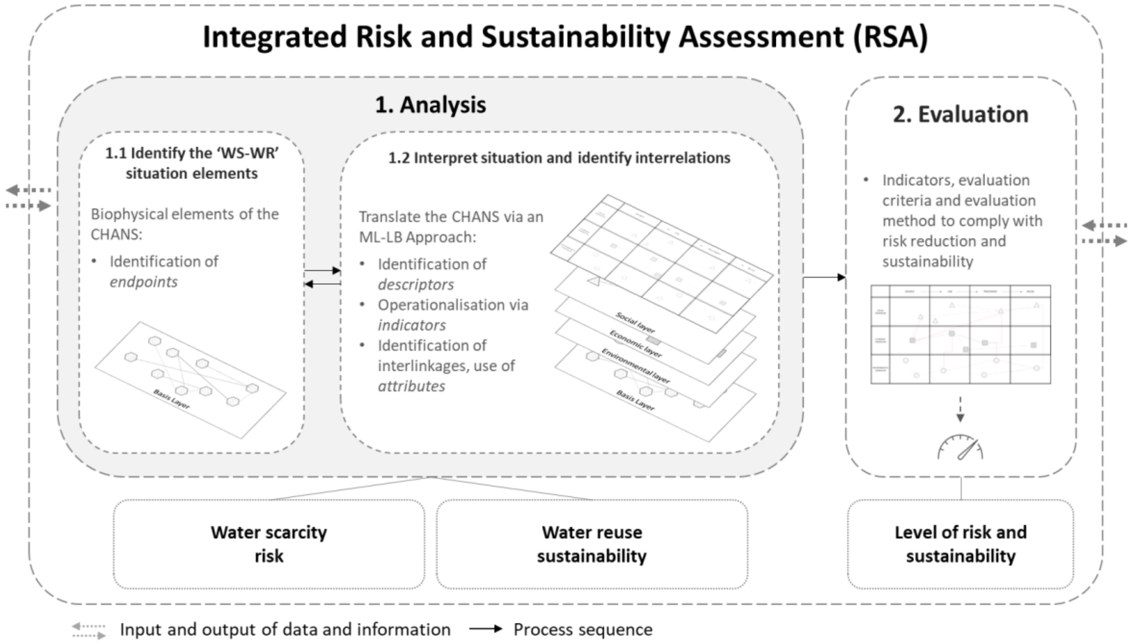

Figure 3.4: Analytical concept embedded in the RSA Framework. Based on Müller et al. (2020).

3.5.2 Exemplification of the analyitical concept

As mentioned, the interpretation of a situation relies on the involved researchers and experts; thus, existing studies of specific cases, including water scarcity and water reuse, can support a generic but detailed enough exemplification of the analytical concept. An overview of the literature shows a plethora of risk- and sustainability-related indicators used in assessments for water resources management (e.g., Collins and Bolin 2007; Muga and Mihelcic 2008; Juwana et al. 2012; Damkjaer and Taylor 2017). Rather than a general literature review, a systematic search was carried out looking for scientific articles that provide a list of indicators used for the evaluation of risk of water scarcity and sustainability of water reuse. The chosen database was Scopus, considering articles written in English before 2020. Table 3.3 presents the search strings and the found records (see the complete list in Annex A). To focus the search and facilitate the filtering process the search terms had to be contained in the title. Articles were then filtered by title and content according to two inclusion criteria: (1) align with the terminology of the RSA (e.g., 'water scarcity' instead of 'water stress', 'reuse' instead of 'reclamation' or 'recycling'), and (2)explicitly mention the indicators used to evaluate risk or sustainability .

As no articles simultaneously assessing risk of water scarcity and sustainability of water reuse were found, three scientific articles were selected. On the one hand, risk components are covered by Collins and Bolin (2007) referring to societal and biophysical indicators to assess vulnerability to water scarcity; and Veldkamp et al. (2016) referring to the exposure component of this risk. On the other hand, Upadhyaya and Moore (2012) provide a list of indicators to assess the sustainability of rural water reuse. These articles were found to satisfy the selection criteria.

Based on the information provided in the articles, corresponding endpoints and descriptors were derived by the authors as well as interlinkages between indicators. The interlinkages were identified manually using a matrix for pairwise comparison between indicators. Interlinkages were assigned based on two criteria: (1) the use of the same attribute (e.g., use of the attribute 'total number of housing units' in indicators 'total housing units' and 'mean housing value'); or (2) correlations between the scores of the indicators (e.g., between 'quantity of wastewater reused' and 'energy consumption for reuse component' or between 'aesthetics (colour, odour)' and 'complaints reported to the authority').

Table 3.3: Literature review search string and results

	Water scarcity risk	**Water reuse sustainability**
Search string	TITLE ("water scarcity" AND (risk OR vulnerability)) LANGUAGE (English) DOCTYPE (ar) AND EXCLUDE (PUBYEAR, 2020)	TITLE ((“water reuse" OR "wastewater reuse") AND sustainability) LANGUAGE (English) DOCTYPE (ar) AND EXCLUDE (PUBYEAR, 2020)
Search results	26	11

3.5.2.1 Defining endpoints and translating them into an information system

The biophysical system proposed by the authors (Müller et al., 2020) was used to specify the endpoints. They mainly refer to water quantity aspects in the water flow categories: source (e.g., available groundwater), use (e.g., water supply and water requirements), treatment (e.g., water in wastewater treatment plant – WWTP), and reuse (e.g., treated wastewater for reuse). These endpoints were also compared with literature on system dynamics approaches for water resources management (e.g., Winz et al. 2009; Yazdandoost et al. 2020).

Descriptors were defined for the endpoints and thematically specified based on the RSA information demand as visible from the indicators gained through the literature review (see following sub-section). Table 3.4 shows selected examples of endpoints in the different water flow categories and their respective descriptors, indicators, and attributes (see the complete list in S2). For instance, in the treatment category, the endpoint related to operational aspects of the WWTP can be described by health and security issues, operational and maintenance costs, and operation standards from a social, economic, and environmental perspective, respectively. Furthermore, a descriptor can be operationalised by more than one indicator, e.g., economic feasibility related to the wastewater treatment is defined in terms of the benefit-cost ratio, as well as the ongoing overall benefits.

Table 3.4: Selected example endpoints, descriptors, indicators, and attributes for a generic WS-WR situation and the RSA. R: Risk-indicator, S: Sustainability-indicator. See the complete example list in Annex B.

Category	Endpoint	Dimension	Descriptor	Indicator	Attribute	Type
SOURCE	**Available groundwater**	Environ-mental	Water resources available for human use	Water crowding index	Daily runoff Water province area Time slice (e.g., 30 y) Return period Climate change projection Total population	R
	...	...	...	...	...	...
USE	**Water resources supplied**	Social	Drinking water supply	Proportion of housing units within municipal water provider service area	Housing units within municipal water Total housing units	R
	...	...	...	...	...	...
TREATMENT	**Wastewater treatment operation and maintenance**	Economic	Economic feasibility	Benefit–cost ratio	Benefits quantification Costs quantification	S
				Ongoing benefits	Benefits to broader community Operational costs	S
	...	...	...	....	...	...
REUSE	**Treated wastewater for human reuse**	Environ-mental	Treated wastewater for reuse in agriculture	Quantity of wastewater reused	Quantity of wastewater reused Total treated wastewater	S
	...	...	...	...	...	...

R: Risk-indicator, *S*: Sustainability-indicator. See the complete example list in S2.

3.5.2.2 Characterising the indicators and analysing their interlinkages

For the LB analysis, a total of 41 indicators[3] were identified and characterised, assigning them accordingly to the specific water flow categories, as shown in Figure 3.3 (see Figure 3.5 and the complete list in Annex B). The analysis involved looking at the type and number of indicators within and across dimensions, and the characterisation of interlinkages according to Table 3.1. Table 3.5 presents the number of indicators and interlinkages behind the required information, and the following subsections describe this information.

Table 3.5: Data of the example system: Number of indicators and interlinkages (il.) according to Table 3.1.

		Indicator Type				Intra-dimensional il.			
	Dimension	R	RS	S	Total	R-R	R-S	S-S	Total
	Social	8	0	7	15	7	0	5	12
	Economic	2	0	4	6	0	0	2	2
	Environmental	3	0	17	20	2	0	12	14
	Total	13	0	28	41	9	0	19	28
Inter-dimensional il.	Social	4	2	25	31	11	2	30	43
	Economic	2	2	20	24	2	2	22	26
	Environmental	2	0	29	31	4	0	41	45
	Total*	4	2	37	43	13	2	56	71
		R-R	R-S	S-S					

Type and number of indicators

Results show an information system characterised by a higher number of environmental indicators, accounting for almost 50% (see Figure 3.5). The social dimension shows a balanced distribution of the R- and S-indicators, contrasting with the economic and environmental dimensions with a prevalence of S- over R-indicators. From a risk perspective, the main share belongs to social indicators (around 60%) with a somewhat balanced distribution of economic and environmental indicators. From a sustainability perspective, there is an almost direct swap in proportions between social and environmental indicators, as 60% of the S-indicators refer to environmental aspects. Thus, social information seems highly relevant from a risk perspective, whereas assessing sustainability relies heavily on environmental aspects.

Overall, no overlapping indicators (RS) were found, and R-indicators characterise only one-third of the entire system attributing the main contribution to S-indicators. This suggests that the data required for the risk and sustainability assessments are different and that sustainability-related aspects majorly define the system's performance.

Regarding the indicators' distribution, environmental indicators are relevant for the source and reuse category of the water flow. In contrast, the use category does not include this type of indicators. Social indicators seem relevant for characterising the use and reuse categories, and economic indicators are distributed evenly from the use to the reuse categories.

[3] Two vulnerability indicators referring to race and ethnicity (Collins and Bolin, 2007) were not included as they were considered to be case-specific for the example addressed in that study. Two economic sustainability indicators (Upadhyaya and Moore, 2012) were repeated for the 'Treatment' and 'Reuse' categories, as they are separated in the RSA Framework.

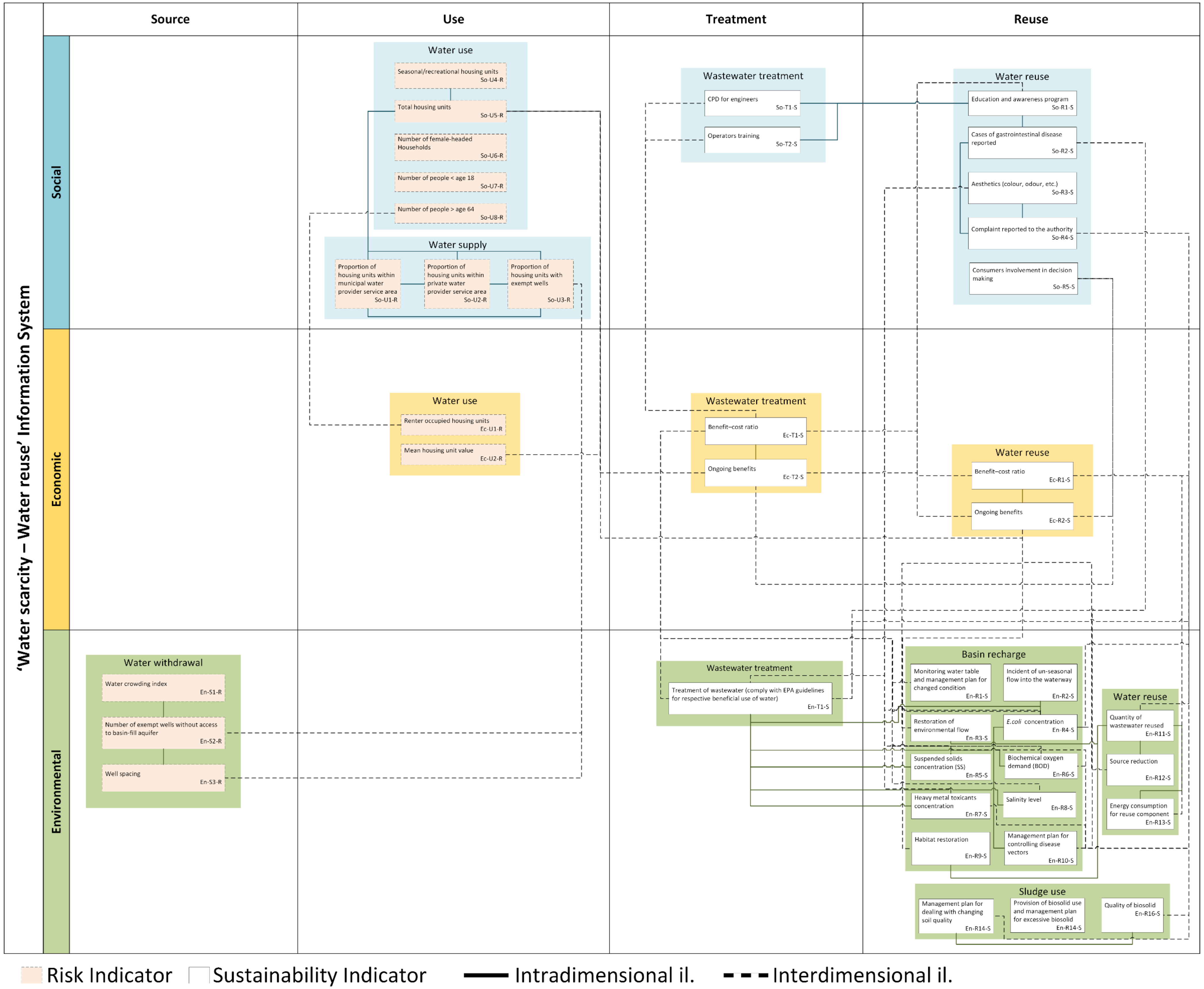

Figure 3.5: Overview of the lane-based visualisation of all layers, the indicators, and interlinkages (il.). Attributes are omitted for space reasons (The details are provided in the online figure; the full list of indicators is accessible in Annex B).

Type and number of interlinkages

From an intra-dimensional perspective, 28 interlinkages (il.) were identified, with a major share of S-S interlinkages (67.8%). However, this share aligns with the number of S-indicators (68.3%), which hampers inferring, at this point, that S-indicators are more interconnected than R-indicators (see following sub-section). It is possible, though, to see that changes in risk indicators seem more relevant from a social perspective. In contrast, the dynamics from a sustainability perspective seem particularly relevant for the environmental dimension.

From an inter-dimensional perspective, 43 il. were identified involving high participation of social and environmental indicators (both involved in 72.1%), whereas economic indicators participate in 55.8% of the interlinkages. All inter-dimensional R-related interlinkages involve social indicators, although they represent only 9% of the inter-dimensional view. Thus, in this example, the R-indicators do not highly influence system dynamics but are highly dependent on social aspects. In contrast, most of the interlinkages involve S-indicators; thus, the inter-dimensional influence becomes more relevant for water reuse than for water scarcity.

Overall, the share between intra- and inter-dimensional interlinkages (around 39.4% and 60.6%, respectively) shows that dimensions are highly interconnected. This interconnectivity majorly characterises the system, where both social and environmental aspects are highly influenced or influencing. Concerning a potential correlation between the type and number of indicators and the interlinkages, even when a similar trend was found at an intra-dimensional level (similar ratio between R- and S-indicators, and R- and S-related interlinkages), this was not maintained on a general level, as the S-related interlinkages greatly prevail over R-related ones. The latter account for 18.3% of all interlinkages, indicating a minor influence of these indicators on the information system. In contrast, the number of interlinkages characterises the information system as being highly dependent on sustainability indicators (particularly social and environmental aspects), as they are involved in the majority of intra- and inter-dimensional interlinkages. Regarding a correlation between risk and sustainability, counting with no RS-indicators and an almost negligible number of R-S interlinkages allows inferring that, under the current representation, no considerable changes in the level of risk are expected by changing levels of sustainability, or vice versa.

Indicator connectivity

A general overview of the average indicator's connectivity in each dimension shows a higher value for environmental indicators (0.44 il. per indicator), followed by the social and economic indicators (0.35 and 0.23 il. per indicator, respectively). However, the top three MII include one indicator of each dimension: "Complaint reported to the authority" (social S-indicator, 11 il.), "Benefit-cost ratio" (economic S-indicator, 11 il.), and "Treatment of wastewater (compliance with guidelines)" (environmental S-indicator, 10 il.). This means that even though economic aspects do not appear as relevant according in general terms, one of their indicators has the highest specific connectivity. Hence, the relevance of this analysis.

3.5.2.3 Overall results

The ML-LB approach can support decision-making, as it provides the following overarching insights from the example WS-WR information system: (a) leverage points for an overall improvement of the risk and sustainability performance of the WS-WR situation are likely to be linked to the sustainability of water reuse rather than the risk of water scarcity; (b) interventions could target social and environmental sustainability-related aspects as they are highly interlinked in the information system; (c) primary interventions related to social aspects are to be planned for the use and treatment categories; (d) environmental interventions should focus on the source and treatment of water resources. Further interpretations could be drawn if more specific questions are placed, reaching even a level of specific performance of indicators, e.g., How influential is the indicator "Quantity of wastewater reused" for social sustainability aspect?

3.6 Discussion

3.6.1 Translating the CHANS into an information system

The identification of CHANS biophysical elements and a direct and organised translation into an information system seems adequate as this needs to be done anyway for assessments. All assessment tasks, from problem framing to selecting evaluation indicators and criteria, occur on an information level. However, the "small" step of interpreting a real-world situation to be analysed and evaluated involves various minor decisions regarding the aspects to include, increasing the subjectivity of the assessment — for instance, the ongoing debate about the appropriate selection of indicators. De Olde et al. (2017) highlight the relevance of transparency and collaboration in the selection process for the success of the assessment. If no proper attention is given to this process, there is a risk of an inadequate assessment where information is derived from indicators that do not necessarily represent the situation or align with the initial aim (e.g., Zijp et al. 2017). Hence, the relevance of moving towards a transparent and systematic approach for identifying the relevant biophysical aspects (endpoints) and required information (descriptors) with the respective metrics (indicators and attributes).

The United Nations Department of Economic and Social Affairs (UNDESA) has recognised the relevance of indicators for policy-making by valuing their incorporation of knowledge from natural and social sciences into decision-making (United Nations 2007). Thus, they are widely used and accepted metrics that allow gathering scattered, siloed and discipline-specific information (Ciegis et al. 2009; Walmsley 2002). Their use as operationalisation elements seems appropriate as they allow remaining connected to different disciplines while including them as part of a broader interdisciplinary assessment, enabling incorporating different knowledge. Zijp et al. (2017) review different methods used in sustainability assessments highlighting that the link between the used metrics and the "*question at hand*" (the aim) could be further improved. Thus, the inclusion of indicators in the analysis phase as elements derived from the translation of the biophysical endpoints should support such an alignment.

When interpreting the results of this analytical concept, it should be considered that indicators are mere operational metrics that do not fully represent the complexity of the situation, where more profound social, economic, and environmental management issues might be overlooked. Their intention is to represent specific parts of the system that are of interest to be evaluated, offering a pragmatic view. This limitation, existing in any indicator-based assessment, is now explicitly evidenced by showing the proportion of the type of indicators and their interlinkages, leading to questions such as: Are environmental aspects underrepresented for the evaluation of risk of water scarcity? What is the relevance of having differences in the number of indicators between the different types? These questions can then be specifically addressed on case-by-case basis to improve existing indicators or derive new ones and refine the interpretation of the evaluation results (i.e., high or low risk and sustainability performance). Ultimately, more profound issues, even related to governance, political and participation aspects could be measured through indicators (e.g., Upadhyaya and Moore, 2012; OECD, 2018), but this would mean an increase in the number of indicators considered for the analysis, aligning with the plethora of indicators found in literature and intensifying the data requirements.

From a systems perspective, endpoints are not different from the elements in CLD or SFD. However, they are named here to differentiate them from the elements composing the information system. Other systems' analysis approaches such as the SES analysis framework (Ostrom, 2009) or system dynamics, have the aim of studying the functioning of a system to understand a real-world situation. Thus, they may support the identification of endpoints and descriptors. However, they do not necessarily narrow down the focus to understand the functioning from a performance point of view. Here indicators are required together with defined thresholds to achieve the desired performance, which can also represent the subjective aims of the involved stakeholders. Thus, there are two strands; on the one hand, assessments supporting decision-making can sometimes be distant or misrepresenting the situation (e.g., focused mainly on environmental aspects). On the other hand, complex systems modelling are challenging to operationalise and present to practitioners. This way, the analytical concept proposed here does not intend to replace other systems thinking approaches but bridge a systems conceptualisation with traditional indicator-based assessments, compromising some level of detail on both sides and providing complementary information.

3.6.2 Supporting decision-making via the analytical concept

Based on the above, the analytical concept derived in this study provides a structured and systematic manner for a transparent transition from the conceptualisation of a WS-WR situation as a system to its assessment based on indicators, bridging the real-world subject of the assessment with the information needs.

The ML-LB approach helps to grasp the idea of translating the biophysical elements of the CHANS into an information system. It allows a general vision of the information system while keeping a view of the different dimensions. As mentioned in section 3.3.2.3, this type of approach has been widely used, succeeding in presenting complex interlinked systems as networks. Furthermore, the evidence-based identification of interlinkages between *indicators* advances towards an integrated characterisation of the WS-WR situation. It allows determining key indicators and data-intensive aspects, supporting, e.g., data prioritisation, indicator selection. This has also been recognised as relevant in other fields dealing with complex systems, e.g., resource nexus (e.g., Laspidou et al. 2020). However, interlinkage directionality, based on features such as causality, was not considered. Examples of this are the identification of balancing and reinforcing loops on CLDs, or the "If-Then" approach considered by Rubio-Martin et al. (2020) for drought management. These causality-driven approaches allow a more accurate representation and understanding of the system's dynamics. For instance, if indicators A and B are interlinked in a direction of A influencing B, the change A leads to a specific change in B, rather than the other way around. In the current status of the analytical concept, A and B are not defined in terms of which is the influencing and influenced indicator. Thus, predicting future changes will only be as accurate as recognising that a change in A might mean a change in B and vice versa.

Additionally, spatial-temporal features were not further detailed in this analytical concept beyond their indirect inclusion via indicators. These features should be minded for the interpretation of the ML-LB results. For instance, annually based indicators such as "Mean annual precipitation" or "Annual water resources extraction" could be considered as relevant as "Net present value", which depends on the project's evaluation horizon for its calculation. This is also an aspect highlighted by Nilsson et al. (2018) for the case of interactions between the SDGs.

Regarding the visual aspects of the analytical concept, conceptual maps are a means of explicitly portraying complexity, as it probably exceeds the capacity to conceptualise it in mental models (Nguyen et al. 2015), especially to analyse existing interlinkages between the system's elements (e.g., Davies and Simonovic 2011; Mirchi et al. 2012; Sterman 2012; Di Baldassarre et al. 2013). They have been recognised as essential modelling tools that support the understanding of the system, model design, identifying leverage points, and communication with stakeholders (Rhoades et al. 2014; Voinov 2018). Here the ML-LB approach can serve as a basis for more sophisticated visualisations of the information system showing all dimensions simultaneously. It allows presenting these dimensions separately, keeping their specific focus unaltered, while visualising the interlinkages between them in a compartmentalised manner providing the *big picture*. However, this relevant visualisation tool needs to be accompanied by a table summarising all the information, awarding flexibility about its content and detail level depending on the aim and audience (e.g., focus on inter-dimensional aspects). The wide use of BPMN in the business sector corroborates the use of lanes for organising, in this case, indicators from different dimensions, in a structured and straightforward manner. Explicitly portraying relationships within the system raises the usefulness of such notation for systems thinking, stressing its relevance for structured and transparent communication of the model (Hinkel et al. 2014; Schlüter et al. 2014). This is relevant for decision-making and inter- and transdisciplinary research in general (Liu et al. 2007; Voinov 2018), as well as building and maintaining trust among stakeholders and the general public in water resources management (Hartley 2006).

Overall, the analytical concept proposed here can support the implementation of international agreements and guidelines such as the Sendai Framework for Disaster Risk Reduction and the Sustainable Development Goals (SDGs). Within the Sendai Framework, it aligns with the priorities for action related to the understanding of risk (primarily the use of baselines and the analysis of information) and the goal of implementing risk reduction measures considering social, economic, and environmental aspects, contributing to the target of increasing the availability of information and assessments. Within the SDGs, this concept relates to goals 6 and 11 by supporting the implementation of water reuse measures and aiming at reducing people affected by water scarcity, and by aligning with the Sendai Framework, respectively.

3.7 Conclusions

Within the frame of an integrated RSA for WS-WR situations, analysis and evaluation tasks should organise and process relevant information for decision-making (Müller et al. 2020). Intending to further advance the analysis, this article brings together perspectives from different disciplines for translating these situations into information systems based on systems thinking interpretation and characterisation and interlinkage of indicators. This results in the derivation of an analytical concept comprising: (1) the identification of relevant *endpoints* in the biophysical system, (2) the use of a multi-layer (ML) approach for the translation into an information system based on *descriptors* and *indicators*, and (3) the use of a lane-based (LB) approach for clear visualisation and analysis of these layers and the respective interlinkages.

The analytical concept bears on interpreting the WS-WR situations as a CHANS and translating it into an information system to comply with the requirements of minimising the risk of water scarcity and maximising the sustainability of water reuse rather than providing a general understanding of the CHANS dynamics. The ML-LB approach uses the sustainability dimensions to develop, process and portray relevant information to guide the RSA for comprehensive and consistent support of decision-making in WS-WR situations. Therefore, it is key to include *indicators*, typically used in evaluations, already in the analysis. The identification of interlinkages between these *indicators* at both intra- and inter-dimensional levels enables extracting information about the social, economic, and environmental perspectives separately or as a whole, as well as identifying the risk- and sustainability-related performances. These results are defined in terms of the type and number of indicators and interlinkages, and the indicator's connectivity. Finally, the information system's visualisation in a compartmentalised manner differentiates the *foci* of each dimension while providing the *big picture*.

This analytical concept allows moving the attention from fully understanding the situation to dealing with the information relevant for its management. The ultimate goal of this is to offer the possibility of optimising data collection by, e.g., prioritising highly interlinked indicators and support the identification of leverage points for the design of interventions. Thus, the added value of an ML-LB analysis is three-fold: (1) acknowledgement and systematisation of the translation from the real-world situation to an information system for the identification of valuable indicators, (2) the delivery of evidence-based information in a structured manner, allowing to explicitly quantify the interlinkages across social, economic, and environmental dimensions, and (3) the application of a map to visualise these interlinkages and support clear communication and knowledge transfer with decision-makers and stakeholders.

Current limitations and improvement points of the proposed analytical concept include (a) a systematic approach to guide the research team in defining relevant *endpoints* and *descriptors*, (b) interlinkage directionality, (c) lack of a database of indicators and their respective attributes that facilitates interlinkage identification; and (d) inherent limitations of indicator-based approaches not fully representing the complexity of the situation. A tool that supports automation could also facilitate the process (e.g., generation of the layers and lanes, counting interlinkages, generating database). This seems an achievable outlook, as data processing here does not involve complicated calculations, and the existing variety of visualisation and data analysis software that could serve as inspiration is broad and widely used (e.g., Tableau®, Qlik®, PowerBI®).

A general outlook of this work is the potential use of the analytical concept beyond water scarcity risk and water reuse sustainability, as its structure is not limited to these types of *descriptors* and *indicators*. Subsequent research could focus on studying the implications of interlinkage directionality and developing a database and software tools that support automation.

3.8 Acknowledgements

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Chapter 4 Framework Testing

This chapter corresponds to the scientific article 3 (see sub-section 1.3.2). It addresses the testing of the integrated RSA Framework in a case study located in Cerrillos de Tamaya, Chile. It builds on the outputs of chapters 2 and 3, focusing on:

- Describing the case study location and adapting the RSA Framework to fit the local context by interpreting the WS-WR situation as a CHANS.
- Translating the CHANS via the ML approach and identifying and characterising interlinkages via the LB approach.
- Evaluating the degree of risk of water scarcity and sustainability of water reuse using the distance-to-target method TOPSIS.
- Discussing case study results to provide feedback for the RSA Framework.

Testing the integrated risk and sustainability assessment (RSA) framework for 'water scarcity – water reuse' situations: The case of Cerrillos de Tamaya in Chile

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Abstract

The projected increase in 'water scarcity – water reuse' situations, the associated risks and sustainability challenges, and trends towards holistic approaches motivate the development of integrated assessment for decision-making. The integrated Risk and Sustainability Assessment (RSA) Framework combines the analysis and evaluation of both risk and sustainability of 'water scarcity – water reuse' situations. This work aims to test the RSA Framework in a case study in Chile. The analysis uses a multi-layer approach and lane-based approach to translate the real-world system into an information system and to determine interlinkages between indicators. The evaluation involves thresholds and weights to calculate risk and sustainability sub-indices and an RSA index applying TOPSIS. The results indicate low interlinkage between risk and sustainability indicators, visibilising the importance of which and how indicators are considered and what they measure. They show a higher than tolerable degree of risk but an acceptable degree of sustainability. The relevance of spatial and temporal scales for the assessment becomes evident. Spatial aspects are key in determining the degree of water scarcity and how the impact of water reuse can be included in its calculation. Temporal aspects complicate the integration of risk (scenario-based) and sustainability (snapshot mode) assessments. The TOPSIS method appears to be suitable for the aggregation of risk and sustainability performance indicators. Altogether, the results show the potential of the RSA Framework for organising and processing information required to support decision-makers addressing 'water scarcity – water reuse' situations from the perspectives of risk and sustainability.

Keywords: risk assessment, sustainability assessment, water scarcity, water reuse, indicators

4.1 Introduction

Water scarcity is a well-recognised problem that is expected to rise in the coming years, either by a decrease in the quantity of freshwater for supply, an increase in its demand, or both (Greve et al. 2018; He et al. 2021). In many cases, water reuse (understood as the use of treated wastewater) is considered a sustainable intervention to reduce the supply-demand gap (e.g., Levy et al. 2014; FAO 2017; Gude 2017; Fito and Van Hulle 2020). However, this might not always be the case, as water reuse measures may fail, among other issues, due to a lack of water resources for reuse (e.g., Beveridge et al. 2017), pressure on the technical system from the concentration of pollutants, or operation and maintenance efforts (e.g., Tran et al. 2017). This raises the question of how to support decision-making about water reuse in water-scarce regions, where both the risk of water scarcity and the sustainability of the water reuse measure are of interest.

Assessments based on various indicators can provide the necessary information to estimate and judge the degree of water scarcity risk and water reuse sustainability (e.g., Upadhyaya and Moore 2012; Veldkamp et al. 2016; Akhoundi and Nazif 2018; Swain et al. 2020). However, addressing both perspectives simultaneously for the same "water scarcity – water reuse" (WS-WR) situation is still a challenge for science and practice (e.g., UNISDR 2015, 179).

The authors have proposed a conceptual integrated Risk and Sustainability Assessment (RSA) Framework and its methodological implementation (Müller et al. 2020, 2022). The main purpose is to collect and organise the available information for a joint indicator-based analysis and evaluation of the degree of the water scarcity risk and water reuse sustainability. The analysis aims at identifying and processing relevant information about the situation (from risk and sustainability points of view) and existing interrelations; whereas the evaluation judges the performance of the situation via thresholds and weights (Müller et al. 2020). The current article tests this assessment approach in a case study of a WS-WR situation in Chile. The results help provide empirical insights on the applicability of the framework to assess the WS-WR situation of the case study as well as to derive possible improvements.

Section 4.2 briefly introduces the generic RSA Framework for WS-WR situations and describes the case study location and context. Section 4.3 presents the empirical results of implementing the RSA Framework to the case study, including analysis and evaluation results, such as the calculations with the multi-criteria method Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS). Section 4.4 discusses the findings of the case study as well as their meaning for the RSA Framework. Section 4.5 ends the paper with conclusions and an outlook.

4.2 Approach

4.2.1 RSA Framework

The integrated RSA Framework proposed by Müller et al. (2020) includes the analysis and evaluation of both risk and sustainability of WS-WR situations to help decision-makers achieve their defined interest or aim (Figure 4.1). The analysis starts with a view of the WS-WR situation as a Coupled Human and Natural System (CHANS), representing fluxes of matter and energy –the biophysical system– and information –immaterial aspects– (Müller et al. 2020). Later, as decisions are made based on information, a multi-layer approach translates the elements of the biophysical system (endpoints) into an information system by assigning specific descriptors and indicators. As the sustainability dimensions guide the RSA Framework, the translation into the information system involves relevant social, economic, and environmental indicators. These indicators are the metrics required to evaluate the performance of the WS-WR situation from the perspectives of risk and sustainability (Müller et al. 2022). They are then portrayed using a lane-based approach that allows differentiating and interlinking social, economic, and environmental indicators (Müller et al. 2022). Finally, the evaluation of the performance of the situation follows a comparison against threshold values via a multi-criteria method (Müller et al. 2022). The information provided by the assessment is meant to indicate current risk and sustainability status or the effectiveness of interventions to reduce risk and increase sustainability.

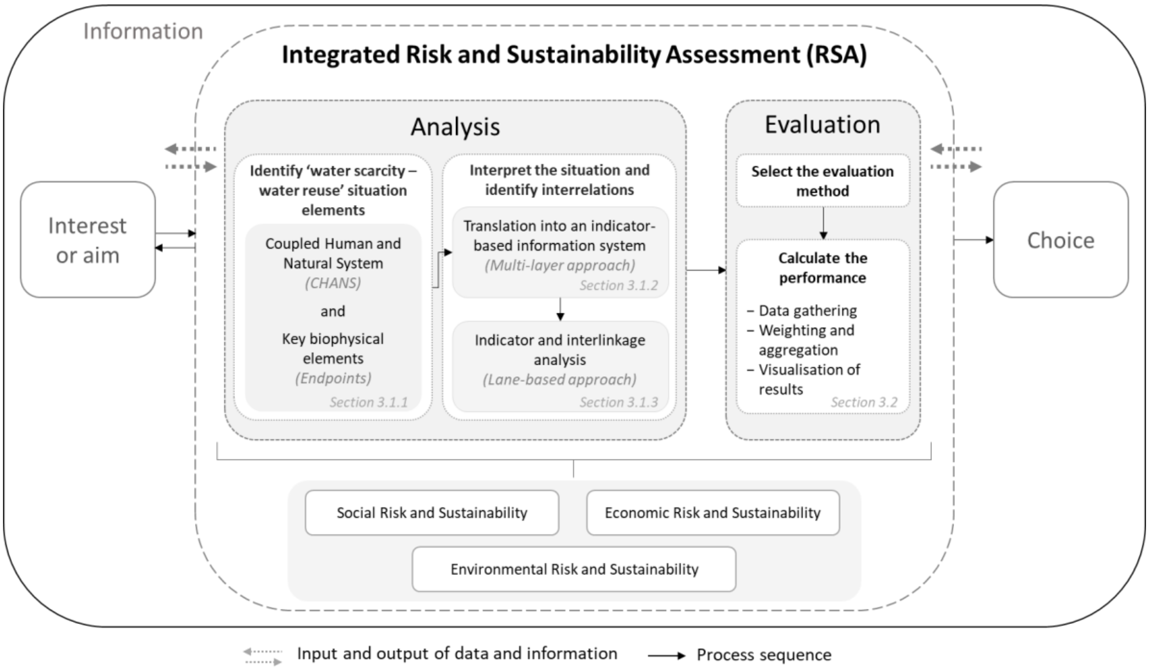

Figure 4.1 Main components of the integrated RSA Framework. Sections in this article presenting the respective results are shown in italics. Modified from Müller et al. (2022).

4.2.1.1 Analysis

The first phase of the RSA Framework is the analysis. The analysis aims at identifying and processing the information about the WS-WR situation that is relevant for evaluating the risk of water scarcity and the sustainability of water reuse. This analysis uses systems thinking from two angles –with systems understood as a set of different elements whose interconnection allows them to function as a whole– (Smithson et al. 2008, 9):

a) CHANS view: This view depicts the elements and flows involved in the WS-WR situation. The WS-WR situation is interpreted as a CHANS, which is particularly useful to differentiate the system's components in biophysical (matter and energy) and immaterial (information) realms. This helps capture the main elements that characterise the situation and should be considered in the assessment and decision-making.
b) Information system view: This view aims at deriving and organising the information of those biophysical elements and flows necessary to assess the WS-WR situation. Since the RSA Framework aims to assess the risk of water scarcity and sustainability of water reuse, not all information related to the CHANS elements and flows is relevant, but only that

information related to risk and sustainability. This means that the CHANS can be represented by specific indicators that will be used to evaluate its performance in terms of risk and sustainability, generating an information system. The latter is understood as a set of interlinked indicators that work as a whole to calculate an RSA index.

Müller et al. (2022) propose a procedure that connects the two systems' views defined above, translating the CHANS representation of the WS-WR situation into the information system. It (1) describes the situation as a CHANS and identifies its biophysical elements (endpoints), (2) translates it into an information system through a multi-layer approach, and (3) applies a lane-based approach to analyse indicators and their interlinkages as a proxy of the interrelations between the social, economic, and environmental dimensions (Figure 4.1). The analysis involves the following steps to fulfil each of the mentioned purposes:

Step 1 – Delineation of the CHANS and identification of endpoints: The assessment begins with describing the real-world WS-WR situation in a manner that can be understood by the involved researchers and practitioners. This task requires input from the decision-maker(s) interested in the assessment and can include further insights from stakeholders. The description of the situation can be structured along with a system's view as follows:

- Describe the WS-WR situation as a CHANS, including the biophysical and immaterial flows. The systems view of the water flows includes four categories: source, use, treatment, and reuse.
- Determine endpoints of the biophysical system. These endpoints represent key biophysical elements of the CHANS (users and processes) [15]. Their identification is case-specific and, hence, up to the researchers and practitioners carrying out the assessment to use literature (top-down approach) or work together with the involved stakeholders (bottom-up approach) (Müller et al. 2022). These endpoints can be viewed as equivalents to the components of the Causal Loop Diagrams or Stock and Flow Diagrams used in systems dynamics. However, the analysis takes this systems view which is then connected with an indicator-based assessment view.

Step 2 – Translation of the CHANS into an information system via the multi-layer approach: Once the endpoints are identified, it is necessary to determine which social, economic and environmental information –related to each endpoint– is relevant to evaluate the risk of water scarcity and the sustainability of water reuse. Thus, the translation aims at building three information-based layers, where each sustainability dimension represents one layer. The procedure involves:

- First, determine social, economic, and environmental descriptors. These descriptors represent, in a generic manner, the information related to each endpoint. It is generic because it does not require detailed specification of e.g., the involved units, the sources of information, and the required calculations to obtain the information [15].
- Second, identify indicators that relate to each descriptor. These indicators further specify the descriptors as they define certain units according to the preferences of the people involved in the assessment (e.g., familiarity with specific metrics and available data). This operationalises the analysis in view of the subsequent indicator-based evaluation.

– Third, characterise each indicator in attributes. These attributes relate to the ways of calculating or determining (in the case of qualitative data) the scores[4] of the indicators, representing the most basic measurements and data needed for these scores[15].

Step 3 – Indicator and interlinkage analysis via the lane-based approach: Once the indicators are defined, the information system can be represented using a lane-based view that includes classifying indicators and the interlinkages between them. The lane-based view allows having a two-dimensional picture of the information system, where each layer of the social, economic, and environmental information from the multi-layer approach represents a lane. The classification of indicators and identification of interlinkages provides an understanding of the interrelations between the different dimensions. This, together with the evaluation results, helps to derive strategies to improve the system's performance via the following analyses:

– Type and number of indicators: This involves classifying each social (So), economic (Ec), and environmental (En) indicator as risk (R), sustainability (S), or joint risk and sustainability indicator (RS), resulting in nine indicator types. The distribution of the types of indicators can indicate the role of social, economic and environmental information (Müller et al. 2022).
– Type and number of interlinkages: This involves identifying interlinkages between indicators according to whether they: (a) possess the same attributes, or (b) have correlations between their scores. Four classes of interlinkages are possible: between two risk indicators (R-R), two sustainability indicators (S-S), one risk and one sustainability indicator (R-S), or two RS-indicators (RS-RS). Here, R-S is equal to S-R, as no directionality is considered. Also, for interlinkages between RS-indicators with R- or S-indicators, they should be considered as R-R or S-S, respectively. The distribution of the different types of interlinkages can indicate which elements are likely to change due to changes in other indicators. For instance, if environmental indicators are mostly connected with social indicators, changes in social aspects might influence the environmental performance, or vice versa (Müller et al. 2022). Interlinkages within (intra) and across (inter) dimensions are recorded and counted using an interlinkage identification matrix to compare the indicators with each other. Interlinkages were notated with an "X" and later represented as lines. Since no directionality is considered, this matrix is symmetric.
– Indicator connectivity: This involves calculating the ratio of the number of interlinkages per indicator group or indicator. Per group means at the level of sustainability dimension (So, Ec, En), or for all R- and S- indicators (across dimensions). The connectivity at an individual indicator level results in an identification and ranking of the most interlinked indicators. These indicators can be considered critical for the system's performance as their high connectivity means they are subject to change if other indicators' scores change or vice versa. Thus, they should be included in the evaluation (given the respective data and threshold availability).

Overall, these analyses can be carried out at different levels (as shown in Table 4.1): at the indicator level, at a dimension level (intra-dimensional, e.g., the general social performance by considering only the social indicators), at an inter-dimensional level (across all dimensions, e.g.,

[4] Score is understood as the measured qualitative or quantitative rate of the indicator, e.g., the score for the economic indicator "Unemployment rate" can vary between 0% and 100%.

the general risk performance across social, economic and environmental dimensions), or at a system's level across all dimensions and including both risk and sustainability (Müller et al. 2022).

4.2.1.2 Evaluation

The evaluation relies on using thresholds that represent a targeted score to compare with each indicator's actual score. This way it is possible to see how far each indicator is scoring from the desired target. Established laws, regulations or guidelines can define these thresholds. For instance, the "Percentage of water resources in storage (compared to historical average)" should be no less than 60% of the maximum capacity of the reservoir (DGA 2012). Or they can be set according to the subjective interests of stakeholders or decision-makers, e.g., the aim for a region is to have an "Unemployment rate" of a maximum of 4%. After comparing all indicators with their respective thresholds, the performance of the system can be calculated through aggregation into an RSA index. This calculation requires specific weighting and aggregation calculations that vary depending on the used methods.

The RSA Framework does not prescribe a particular evaluation method, as it recognises the variety of methods available for this task, e.g., within multi-criteria decision-making methods (Müller et al. 2020). It allows using the calculation method that suits the preferences of the user on a case-by-case basis (Müller et al. 2020). Therefore, the next paragraphs will move from a generic approach description followed for the analysis to a more detailed and case-specific description of the evaluation approach chosen for the testing of the RSA Framework.

In this case, the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method was chosen, as it provides a simple, easy-to-use, and adaptable setup suitable for decision-makers unfamiliar with multi-criteria evaluation methods (Kalbar et al. 2012; Garcia-Bernabeu et al. 2020). MS Excel was used for the setup and calculations (more details on the calculation steps and results are provided in SM-A). Although there is no direct comparison of different alternatives, in this case, a multi-criteria evaluation method was chosen for the evaluation, opening the possibility for its use in other cases that explore multiple alternatives. The TOPSIS method is a distance-to-target approach that calculates the distance of each point (or alternative) to the best and worst scores (Yoon and Hwang 1995). An aggregated index determined by the relative closeness to the target represents the overall performance.

As this is the first assessment of this sort for the selected water reuse project, the assessment *ex-post* aims to establish a baseline for comparisons of performances of water reuse in the future. Likewise, as there is no previous data for comparison, the water reuse alternative is compared with best-case and worst-case alternatives. Using TOPSIS to evaluate these 'ideal alternatives' alongside the real alternative establishes the cases of a best-case scenario ('ideal best') and worst-case scenario ('ideal worst'). In the 'ideal best', all indicators perform with the best score compared to the thresholds, whereas in the 'ideal worst', all indicators perform with the worst score. Thus, the performance of the real alternative moves between these two extreme cases.

For the evaluation, the following considerations regarding data gathering, weighting and aggregation of indicators, and visualisation of results are important:

Parameterisation of data

Data for indicators can be gathered from various sources, primary sources including directly measuring water flow, community surveys, and interviews, or secondary sources including annual reports from companies and government. Given travel limitations in 2020, data for the indicators were collected mainly from secondary sources, i.e., a report about the water reuse project, reports from ministries, the regional government and NGOs, and international organisations (World Bank and OECD). In addition, an unstructured remote interview (in Spanish) was carried out on the 20th and 21st of May 2020 with a local stakeholder. This interview provided specific and historical knowledge of the case as well as societal information about the WS-WR situation in general. The interviewee was also specifically asked about the score of selected indicators.

Indicators were selected based on data availability and thresholds, as these are basic requirements for the evaluation. Thus, the long list of indicators used in the analysis was filtered with this criterion and all complying indicators (with data and threshold) were selected for the evaluation.

Determination of thresholds

Thresholds can be determined by decision-makers, experts, or other involved stakeholders via participatory means, such as workshops and focus groups, or directly taken from regulations and guidelines (Aires and Ferreira 2019). In this case, the thresholds were taken from literature and regulations or were based on the interview with the local stakeholder. Data for thresholds were found in the Chilean regulation and international guidelines (e.g., WHO) and were adapted to the case study by the authors (especially for the qualitative indicators, as data was scarce). For the qualitative data, two scoring scales were mostly used: 1-5 Likert scales, representing scores of "very low", "low", "medium", "high", and "very high", respectively, and a binary "Yes-No" scoring. Thresholds were only defined for indicators with available data.

Weighting and aggregation

Considering that both risk and sustainability are equally relevant according to the RSA Framework and as a first test of the ex-post assessment, equal weight was attributed to their respective sub-indices in the aggregation of the final index. Likewise, weights were equal between the dimensions as well as for all indicators within each dimension (

Figure 4.2). Other circumstances could have allowed the use of participatory subjective methods to assign weights via, e.g., the Analytical Hierarchy Process (AHP).

A two-tier aggregation scheme guided the individual evaluation of R- and S-indicators separately through aggregation into a sub-index score for risk and sustainability, respectively, followed by the final aggregation of these two sub-indices into a single-score RSA index (

Figure 4.2).

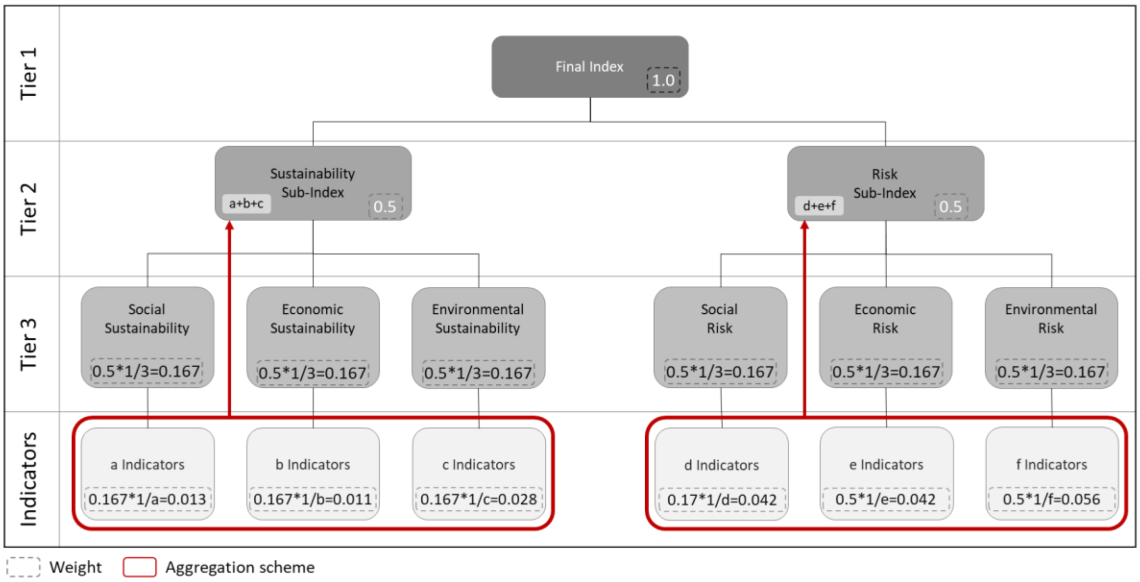

Figure 4.2 Weighting and aggregation scheme. Letters a-f represent the number of each indicator type. No RS indicators were evaluated.

Visualisation of evaluation results

The evaluation results are visualised in both an aggregated and disaggregated manner. A graph locating the risk sub-index in the Y-coordinate (ordinate) and the sustainability sub-index in the X-coordinate (abscissa) with a scale from 0.00 to 1.00 presents the aggregated final index (Figure 4.5). In this graph, the 'ideal worst' case is located in coordinate (0.00; 0.00) and the 'ideal best' in coordinate (1.00; 1.00).

In the disaggregated representation, the performance for each indicator is depicted using traffic light colour-coding. The colour categories were defined following Benavides et al. (Benavides et al. 2019). The threshold ranges were divided into three categories: red, yellow, and green. Red means severe underperformance, yellow means slight underperformance, and green indicates compliance with the threshold. Then, the score value for each indicator was compared to the threshold categories and coloured accordingly (see the full list in SM-E). These results were included in the lane-based visualisation.

4.2.2 Case study site

In Chile, water scarcity issues have been widely reported, especially due to the "mega drought" in recent years (Aitken et al. 2016; Garreaud et al. 2020; Fuentes et al. 2021). In the central-northern regions of the country, the climate is arid and semi-arid, and the available water as annual mean runoff is 510 m^3/person/year (Valdés-Pineda et al. 2014; MOP and DGA 2016). According to the FAO, this can indicate a situation of chronic water scarcity (FAO (Food and Agriculture Organisation of the United Nations) 2018). Regarding water demand, the main water-consuming sectors are the agricultural and industrial sectors (Aitken et al. 2016; MOP and DGA 2016), followed by the domestic and municipal, as most of the Chilean population lives in the central regions (Valdés-Pineda et al. 2014; INE n.d.). The overlay of population growth and water-intensive production has caused a situation of increasing water scarcity in the area (Valdés-Pineda et al. 2014). Projections show a tendency toward drier conditions (Fuentes et al. 2021), thus increasing the likelihood of water scarcity situations. This has led to the rise of several national and regional initiatives to design and implement new measures for water resources management. Among these initiatives, water reuse measures have been included as an important solution to consider (e.g., MOP 2020a).

In 2018, the first water reuse project for productive use in agriculture was inaugurated in the central-northern area of Chile, in the Coquimbo Region (Díaz Moya and Broschek Santelices 2018). The public-private partnership Fundación Chile led the design and implementation of this project, which was funded by the regional government(Díaz Moya and Broschek Santelices 2018). This region is well known for experiencing water scarcity situations. Since 2008, the General Water Authority (DGA) division of the Ministry of Public Works (MOP) declared water scarcity in the Coquimbo Region 28 times, representing almost 20% of the total emitted decrees (DGA 2021) (more details on how these decrees are emitted is given in Section 4.3.3). This situation has heavily affected the agricultural sector, given its high demand for water resources. According to the Office of Agricultural Studies and Policies (ODEPA) of the Chilean Ministry of Agriculture, the forest and agricultural sector in this region is characterised mainly by crops for livestock fodder production (54.4% of the total forest and agricultural land in the region) (ODEPA 2019). This sector happens to be the most water-demanding sector for consumptive use (i.e., consumption of water without restitution requirements) (Díaz Moya and Broschek Santelices 2018).

Due to an interest in assessing the risk of water scarcity and the sustainability of the water reuse measure after its implementation, the location of the aforementioned water reuse project from 2018 was chosen as the case study site to test the RSA Framework.

The study site is located in the town of Cerrillos de Tamaya (Figure 4.3). The area is cold and semi-arid with temperatures ranging between 10 and 17^{o}C and an average annual accumulated precipitation of 104 mm (Montecinos et al. 2016; MOP 2021). Water supply in this region relies heavily on groundwater in addition to different reservoirs and a network of canals that provide drinking water and water for irrigation (Salinas et al. 2016). In this case study, treated wastewater is used to irrigate half of a 12-ha agricultural field of alfalfa crops; the other half is irrigated with water from the Recoleta reservoir canal network. Cerrillos de Tamaya is located in the coastal catchment between the Elqui and Limarí rivers (Costeras Entre Elqui and Limarí), whereas the Recoleta reservoir is located in the neighbouring catchment of the Limarí River. This means that the agricultural fields in one catchment are irrigated with water from another catchment.

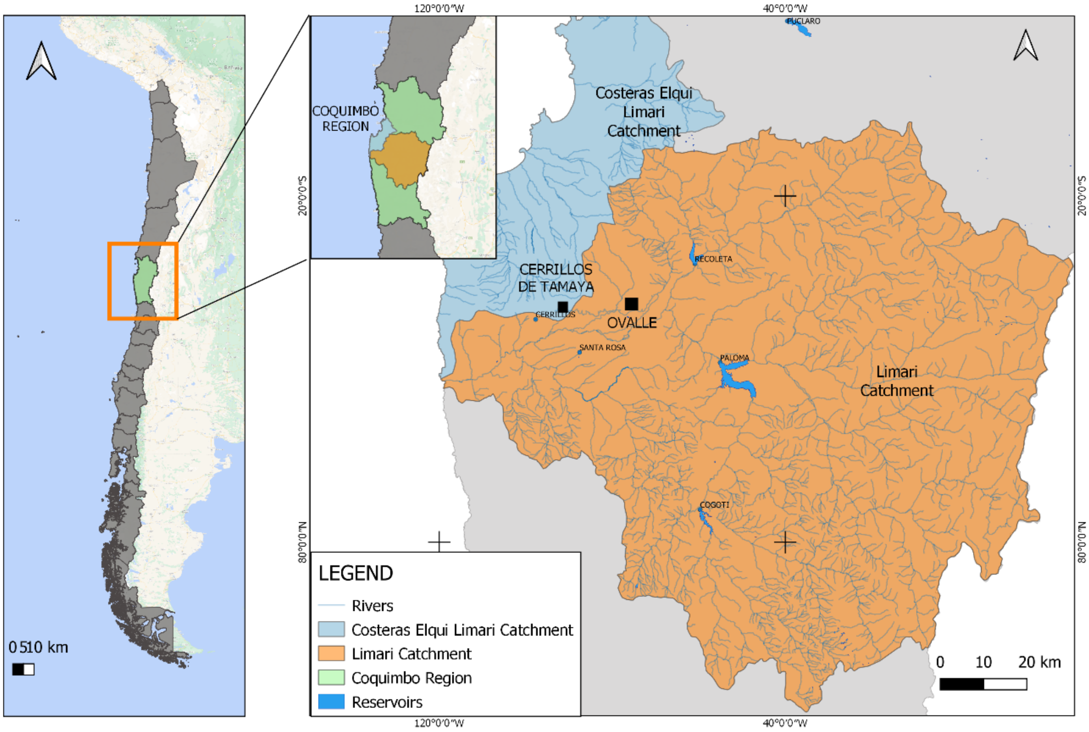

Figure 4.3 Study site in the Coquimbo Region depicting the coastal catchment Costeras Entre Elqui and Limarí, with the location of Cerrillos de Tamaya, and the Limarí River catchment, with the location of the Recoleta reservoir. Map by Ana María Sánchez Higueras.

For the project in Cerrillos de Tamaya, Fundación Chile carried out a technical and economic feasibility study to use the outflow from a rural Wastewater Treatment Plant (WWTP) to irrigate the 6 ha of alfalfa crop for livestock fodder. The WWTP, located 50 m east of the field (uphill), provides treatment services to around 2,900 inhabitants of the area and is managed by the local Rural Sanitary Services association (SSR, formerly known as "Rural Potable Water" – APR) (Díaz Moya and Broschek Santelices 2018). These SSRs are normally managed by the local community forming committees or cooperatives under the authority of the Ministry of Public Works and the regional sanitary authority (MOP 2020b). The project involved key stakeholders including the farmer whose crops would be irrigated through water reuse and representatives from the SSR (the farmer was the president of the SSR committee at that time), Regional Government, Ministry of Public Works, Ministry of Agriculture, and Ministry of Health, as well as technical expertise from companies and academia (Díaz Moya and Broschek Santelices 2018). The aim was to set an example that could be replicated in other locations in Chile experiencing water scarcity.

The water reuse technical feasibility study included the analysis of the water quality to comply with the national regulation (DS90/200), a water storage solution, and the development of an irrigation plan and system to fulfil the alfalfa crop water requirements. The WWTP uses an activated sludge technology with an outflow ranging between 4.0 – 6.0 L/s and complies with the necessary quality requirements for the irrigation of fodder crops (Díaz Moya and Broschek Santelices 2018). Through the reuse measure, the water is no longer discharged into a gorge nearby but is instead accumulated in a pond with a capacity of 3,000 m^3 that allows implementing a three-day irrigation plan for the field (2 ha/day) (Díaz Moya and Broschek Santelices 2018).

From an economic perspective, a business model was agreed upon between the farmer and the SSR, in which the farmer takes full charge of the operation and maintenance of the reuse system and, in return, provides a percentage of the alfalfa sales to invest in the WWTP. The implementation costs of the water reuse measure were covered by Regional Government funds; otherwise, the economic study showed a payback time of 2 to 2.5 years for the investment in implementing the water reuse measure (Díaz Moya and Broschek Santelices 2018). Thus, after being determined technically and economically feasible, the water reuse measure was implemented in 2018 and has continued operating since.

Based on this existing system, the RSA Framework is applied to assess the degree of water scarcity risk and water reuse sustainability in an *ex-post* manner. The aim is to provide a situational snapshot based on which potential intervention points to reduce risk and increase sustainability can be derived.

4.3 Results

4.3.1 Analysis

4.3.1.1 Description of the WS-WR situation as a CHANS

The WS-WR reuse situation of Cerrillos de Tamaya was described as a CHANS with a focus on the flows of water from the "Source" to the "Reuse" (Figure 4). The system presents the circular flow of water resources linearly, following the categories of source, use, treatment, and reuse (Müller et al. 2020). The source includes both catchments, as the Limarí catchment provides water to irrigate half of the case study's farm field (agricultural use). In contrast, the coastal catchment supplies water for domestic use that is treated and reused to irrigate the other half of the field.

The implementation of the RSA in the case study also meant including relevant stakeholders that were involved in the water reuse project led by Fundación Chile and known actors for the source and use categories; no additional stakeholder analysis was carried out. These stakeholders mainly refer to public authorities from different ministries, such as the Superintendency of Sanitary Services and the General Water Authority from the Ministry of Public Works, the Agricultural and Livestock Service from the Ministry of Agriculture, the Rural Sanitary Services (SSR) association, civil society, and the farmer from the field reusing the water, among other local stakeholders (e.g., local sanitary company, research institutes).

From the CHANS view, the authors derived endpoints for the assessment. The results of this step are presented in a tabular manner with the results of the multi-layer approach, where each layer is represented as a column of the table: Endpoint, Descriptor, Indicator, and Attribute (Table 4.2).

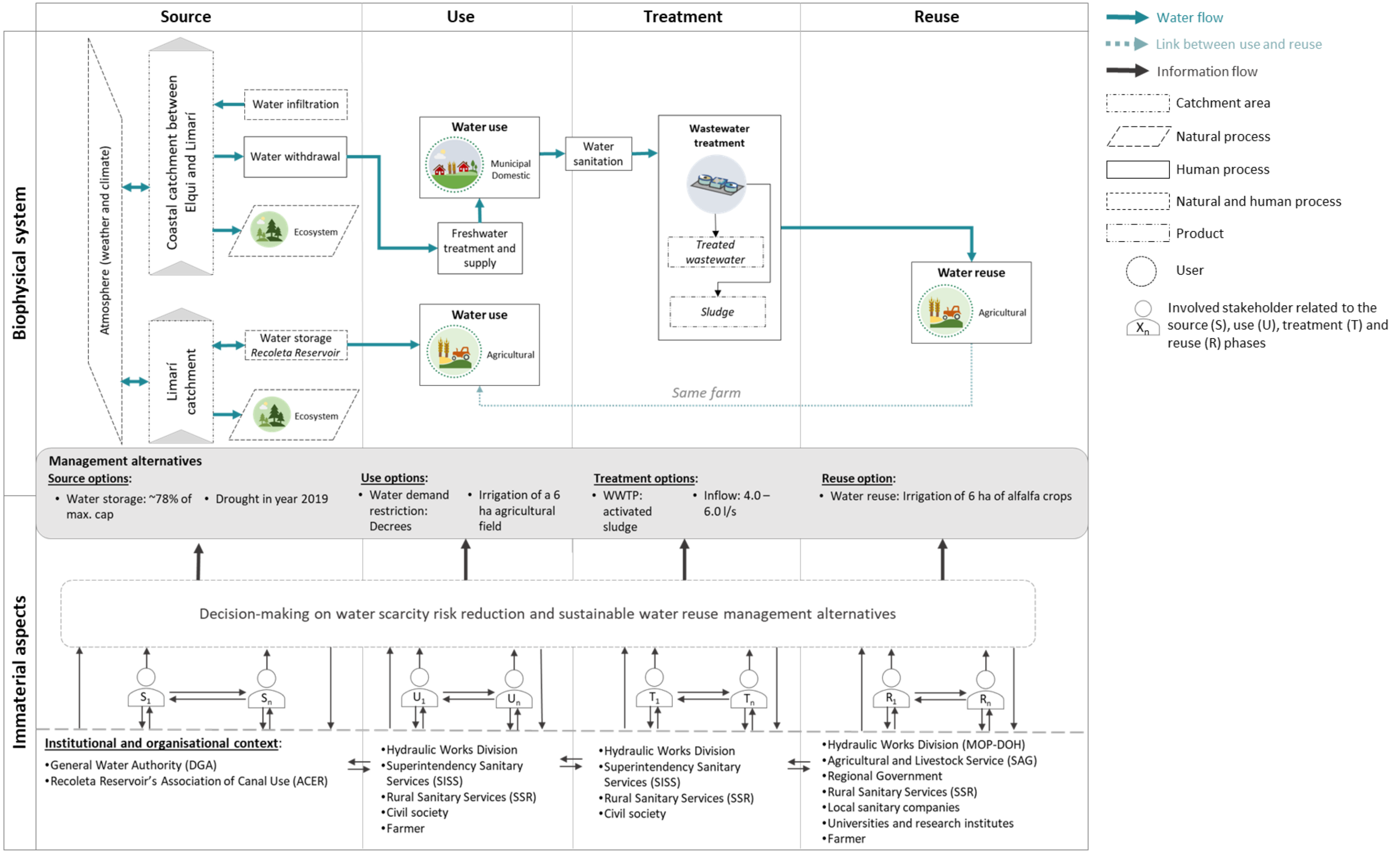

Figure 4.4 System for the case of Cerrillos de Tamaya. Modified from Müller et al. (2020)

4.3.1.2 Multi-layer approach

The conceptualisation of the biophysical section of the system in Figure 4 was used as the basis layer for the identification of endpoints and the subsequent determination of descriptors, indicators, and attributes. Table 4.2 presents an example list of these system elements (see the full list in SM-B).

Indicators were directly taken from literature or adjusted to the case study's conditions, particularly when detailed data was not available as a current score or as a threshold value. These adjustments are referred to as "adapted from [source]" when the name or units are different from the original source or as "determined by authors" when indicators were added after being considered relevant for the RSA. For instance, the economic S-indicators "Budget allocation for training and capacity building" was adapted from Basurko and Mesbahi (Basurko and Mesbahi 2014). Rather than having the total costs (in EUR/year) for training, the term "allocation" was added to change the indicator from a specific numeric score to a general understanding that this point has been considered and that there are funds available to cover training and capacity building. Likewise, Basurko and Mesbahi (Basurko and Mesbahi 2014) use detailed economic information that was not available for this case study; thus, the information was summarised as a different indicator: the economic S-indicator "Existence of adequate funding for treatment". Other examples of indicators of particular interest "determined by authors" were the existence of technical and economic feasibility studies, which are commonly required before the implementation of projects, or the assessment of awareness and perception in social studies (e.g., Lähtinen and Myllyviita 2015; Maleksaeidi et al. 2015). These adjustments were also compared with and driven by information drawn from the interview and meetings with Fundación Chile; for instance, the interviewee mentioned that *"[…] there is enough funding for treatment as all users become associates of the Rural Sanitary Services and are charged with a tariff for drinking water and sewage that goes to a common fund for expenses. If not paid, they are removed as associates. […] Every year one or more trainings are organised depending on the [operational] needs*". However, financial data was not public nor was it shared. Thus, it was necessary to adapt the economic S-indicators and rely on generic qualitative data.

4.3.1.3 Lane-based approach

The ML translation resulted in a total of 67 indicators to include in the lane-based analysis. The analysis results for the type and number of indicators and interlinkages and specific indicator connectivity are described below. Table 4.1 presents the number of indicators and the number of intra- and inter-dimensional interlinkages per type and category. As there are no RS-indicators, RS-RS interlinkages were not analysed.

It is important to mention that all the analysis results presented here refer to the current information chosen to represent the system. Thus, a change in the number and type of indicators can considerably change the analysis results.

Table 4.1 Number of indicators and interlinkages considered for the analysis.

		Indicator Type				Intra-dimensional il.			
	Dimension	**R-indicator**	**RS-indicator**	**S-indicator**	**Total**	**R-R**	**R-S**	**S-S**	**Total**
	Social	10	0	15	25	14	6	23	43
	Economic	7	0	15	22	1	4	15	20
	Environmental	9	0	11	20	12	0	13	25
	Total	**26**	**0**	**41**	**67**	**27**	**10**	**51**	**88**
Inter-dimensional	**Social**	24	11	28	63	38	17	51	106
Inter-dimensional	**Economic**	16	1	22	39	17	5	37	59
Inter-dimensional	**Environmental**	16	10	26	52	28	10	39	77
Inter-dimensional	**Total***	**28**	**11**	**38**	**77**	**55**	**21**	**89**	**165**
		R-R	**R-S**	**S-S**					

il: Interlinkage; R-R: Risk-Risk il.; R-S: Risk-Sustainability il.; S-S: Sustainability-Sustainability il.

*Sum of all interlinkages for each indicator type divided by two to avoid double counting as one interlinkage involves two indicators.

Type and number of indicators

The system is described by a rather balanced distribution of social, economic, and environmental indicators, representing 37.3%, 32.8%, and 29.9% of the entire system, respectively (Figure 4.6). All three dimensions present a prevalence of S- over R-indicators, where sustainability-related information describes more than 60% of the information about the system's performance. This is particularly noticeable in the economic dimension, where S-indicators account for 68.2% of the information. In contrast, in the environmental dimension, the proportion is more balanced (45.0% risk-related and 55.0% sustainability-related). No RS indicators were listed; thus, no direct overlapping information between risk and sustainability can be identified. Overall, the risk of water scarcity is mainly described by social and environmental aspects, whereas sustainability of water reuse relies mostly on social and economic aspects. Thus, social information is a defining component of this assessment.

Concerning the indicators' distribution along with the process categories, environmental indicators are particularly relevant for the source and treatment categories (Figure 4.6). Economic aspects seem relevant for the treatment category as well, whereas the use category largely relies on social information with a minor contribution of environmental aspects. Social and economic aspects mainly describe the reuse category, and the environmental aspects are more involved in the treatment category, describing the performance of the output of the WWTP that then becomes the input of the reuse category.

Type and number of interlinkages

Interlinkages within (intra) and across (inter) dimensions are represented as lines in Figure 4.6. Table 4.3 shows an example of the interlinkage identification matrix (complete version in SM-C). For instance, according to Tang et al. (Tang et al. 2013) there is a connection between people's awareness and perception of water scarcity situations, which can apply, in this case, to the indicators for awareness and perception of water scarcity (example "A" in the matrix).

Another interlinkage between the economic losses caused by water scarcity and the awareness and perception of this situation can be derived (example “B”) from Deh-Haghi et al. (Deh-Haghi et al. 2020). They mention that awareness of water scarcity and its negative consequences, such as economic losses, could probably relate to improving the perception of water reuse. A different example is a link between the “Level of water scarcity” and the “Positive perception about water reuse” based on the statement of the interviewee when referring to the perception of water reuse under the water scarce conditions of the area (example “C”): “*There is a positive attitude towards water reuse, but changes are slow*”. Other interlinkages were defined based on the use of the same information, for instance, between the “Percentage of operating and maintenance costs coverage” and “Existence of adequate funding for treatment” as the operation and maintenance costs need to be considered to determine the adequacy of the funds available.

At an intra-dimensional level, 88 interlinkages (il.) were identified, with a major participation of S-S interlinkages (58.0%), followed by R-R (30.7%) and finally R-S (11.4%). Interlinkages involving social indicators account for the majority of intra-dimensional interlinkages (48.9%), followed by environmental il. (28.4 %), and lastly by economic il. (22.7%). This means that social information is more interlinked than the other dimensions. Regarding S-S il. in general, they are mainly present in the social and economic dimensions, whereas R-R il. are similarly relevant from a social and environmental perspective. The relation between risk and sustainability is minor across all dimensions. The proportional prevalence of S-S il. may correlate with the predominance of S-indicators; thus, it cannot be inferred at this point that S-indicators are more interlinked than R-indicators, and a connectivity analysis is, therefore, necessary (see next subsection “Indicator connectivity”).

From an inter-dimensional perspective, 77 il. were identified, with major participation of social indicators (involved in 81.8% of the il.) followed by environmental and economic indicators (involved in 67.5% and 50.6%, respectively). Overall, S-S interlinkages account for almost 50% of the total inter-dimensional interlinkages, followed by R-R il. (36.4%) and R-S il. (14.3%). S-S il. mainly involve social and environmental indicators, which is also the case for R-S il., indicating a greater connection between these dimensions in comparison to the participation of the economic dimension. The distribution of interlinkages also shows that the influence between the dimensions is more relevant for the sustainability of water reuse than for the risk of water scarcity.

Table 4.2 Multi-layer approach in a tabular layout, including example endpoints, descriptors, indicators, and attributes. So: Social, Ec: Economic, En: Environmental, "…": Ellipsis. Full table in SM-B.

Category	Endpoint	Dim.	Descriptor	Indicator	Attribute	Type
SOURCE	**Available surface water**	En	Quantity of surface water resources available for human use	Ratio of water resources in storage	Average quantity of water resources in analysed period over the past 30 years	R
					Quantity of water resources in assessed period	
			Situation of water scarcity	Existence of an emitted water scarcity decree	Number of water scarcity decrees emitted by the Water Authority in the assessed period	R
				Level of water scarcity	Quantity of water resources available for human use	R
					Quantity of water resources demanded for agricultural irrigation	
		Ec	Costs of water withdrawal	Coverage of water withdrawal costs	Costs of water withdrawal	R
					Budget allocated for water withdrawal	
	…	…	…	…	…	…
USE	**Used water resources**	So	Retaining agricultural function and structure in water-scarce conditions	Retaining agricultural function in water-scarce conditions	Agricultural production in a non-water-scarce year	R
					Agricultural production in a water-scarce year	
				Retaining agricultural structure in water-scarce conditions	Employment related to agriculture in non-water-scarce year	R
					Employment related to agriculture in water-scarce year	
					Productive land in a non-water-scarce year	
					Productive land in a water-scarce year	
		En	Water use efficiency	Water use efficiency	Water losses during irrigation	R
					Total water used for irrigation	
	…	…	…	…	…	…
TREATMENT	**Wastewater treatment plant operation and maintenance**	So	Worker's health and security measures	Complying health and safety practices to protect workers	Total inspections in a year	S
					Total inspections approved in a year	
		Ec	Economic feasibility	Existence of an economic feasibility study	Number of economic feasibility studies	S
	…	…	…	…	…	…
REUSE	**Water resources for reuse**	So	Awareness of water reuse	Water reuse awareness	Total population in study area	S
					Population reporting knowing about the water reuse measure	
	…	…	…	…	…	…

Table 4.3 Examples of the interlinkage identification matrix So: Social, Ec: Economic, En: Environmental, R-ind: Risk indicator, S-ind: Sustainability indicator, "…": Ellipsis

Dimension	Indicator	Social				Economic		Environmental		Count
		Awareness of water scarcity *(So. R-ind.)*	Perception of water scarcity *(So. R-ind.)*	Positive perception about water reuse *(So. S-ind.)*	⋮	Economic loss due to water scarcity *(Ec. R-ind.)*	⋮	Level of water scarcity *(En. R-ind.)*	⋮	
Social	Awareness of water scarcity *(So. R-ind.)*	-	A	B		B				3
	Perception of water scarcity *(So. R-ind.)*	A	-			B				2
	Positive perception about water reuse *(So. S-ind.)*	B		-		B		C		3
	…									
Economic	Economic loss due to water scarcity *(Ec. R-ind.)*	B	B	B		-				3
	…									
Environmental	Level of water scarcity *(En. R-ind.)*			C				-		1
	…									

Overall, 165 il. were identified, with a major share of intra-dimensional il. over inter-dimensional il. (53.3% over 46.7%). This means that, in this case, influences between dimensions are not as prevalent as within them, despite being considerably interlinked. Here, social and environmental indicators participate in most interlinkages (64.2% and 46.7%, respectively), with economic indicators only participating in just over a third of the interlinkages. Most interlinkages correspond to the S-S type (53.9%) followed by R-R (33.3%) and lastly, R-S (12.7%). Thus, sustainability aspects are more interlinked, revealing that the sustainability of the water reuse is more influential/influenced than water scarcity risk aspects for this WS-WR information system. As no RS indicators were identified and risk and sustainability aspects are minorly related, it is not expected that changes in the performance of R-indicators significantly influence the performance of S-indicators or vice versa.

<u>Indicator connectivity</u>

In general, considering all indicators and interlinkages per dimension, the social dimension presents a higher connectivity value with an average of 4.24 il. per indicator, followed by environmental and economic connectivity (3.85 and 2.68 il. per indicator, respectively). The top three most interlinked indicators belong to the first two dimensions (see the full list in SM-D), with the first one being "Level of water scarcity" (environmental R-indicator) with 20 il., followed by the social R-indicators, "Awareness of water scarcity" (11 il.), "Retaining agricultural function in water-scarce conditions" (10 il.), and "Retaining agricultural structure in water-scarce conditions" (10 il.), and the social S-indicator "Positive perception about water reuse" (10 il.). The analysis shows that the top most interlinked indicators correspond to R-indicators although S-indicators largely describe the system and are generally more interlinked. This reveals the relevance of the indicator connectivity analysis at different levels, as there are contrasts between the aggregated view and a detailed, i.e., indicator-specific, view.

However, looking at the top 30 most interlinked indicators, the preponderance of S-indicators (63%) over R-indicators (37%) is noticeable. Likewise, most indicators belong to the social dimension, followed by an equal distribution between the economic and environmental dimensions. Thus, the indicator and interlinkage analyses provide a broad overview that can be further specified by the indicator connectivity analysis for a well-rounded view of the information. For instance, here, it allows the analyst to recognise that addressing sustainability aspects (especially social-related) might support the improvement of the performance of the system. Still, a key element of the performance corresponds to a risk aspect directly linked to the degree of water scarcity and the use of water in agriculture.

4.3.2 Evaluation

The data-gathering process yielded 45 indicators with both scores (~67% of the total originally identified) and corresponding threshold values (see the full list in SM-E). These indicators were used to evaluate the WS-WR situation. Table 4.4 shows the number of R- and S-indicators included and not included, per dimension, in the evaluation. Overall, most data were missing for R-indicators and the environmental dimension. In contrast, data for economic indicators were mostly available (as it was merely qualitative, e.g., there was no access to actual financial data). However, data were available for most of the top 15 most interlinked indicators, except for the case of three social R-indicators: "Awareness of water scarcity", "Controllability of impacts of water scarcity", and "Perception of water scarcity", where data should be gathered by direct consultation with the community (via e.g., survey, interviews).

Table 4.4 Summary of the number of indicators used and not used in the evaluation.

Dimension	No. of indicators evaluated			No. of indicators not evaluated			Total indicators
	Risk	Sustainability	Total	Risk	Sustainability	Total	
Social	4	13	17	6	2	8	25
Economic	4	15	19	3	0	3	22
Environmental	3	6	9	6	5	11	20
Total	11	34	**45**	15	7	**22**	**67**

As part of the TOPSIS procedure, the fictitious 'ideal best' and 'ideal worst' scores were determined for each indicator according to its respective thresholds, represented by upper and lower limits. Indicators were also categorised as 'cost' or 'benefit' based on the relationship between these fictitious scores and their upper and lower limits. Additionally, to establish a more achievable target state than the 'ideal best' (i.e., full compliance of thresholds), a 'minimum desirable' alternative was defined, in which each indicator's score represents at least two-thirds of its respective 'ideal best' threshold score (see details of the TOPSIS results in SM-A). This 'minimum desirable' alternative can represent the degree of risk and sustainability decision-makers would tolerate for a particular assessment. This alternative was included in the TOPSIS calculations and presented together with the case study performance, as shown in Figure 4.5.

The final RSA index scored 0.70 for the case study and 0.78 for the minimum desirable case. This index represents the aggregated score for both risk and sustainability and shows that, overall, the desired degree of sustainability and risk has not yet been achieved. For the sustainability sub-index, the case study score of 0.71 was the same as that of the minimum desirable case (0.71), thus indicating that a minimum desirable degree of sustainability for water reuse has been achieved. However, for the risk sub-index, the case study score (0.68) was lower than that of the minimum desirable case (0.89), indicating that measures are still necessary to reduce the risk of water scarcity and improve its sub-index score.

On the indicator evaluation level, the worst scores (furthest from the 'ideal best') corresponded to: "Population below poverty line" (social R-indicator), "Awareness about water reuse" (social S-indicator), "Generation of new funds to cover additional capital costs" (economic S-indicator), and "Existence of an emitted water scarcity decree for the area" (environmental R-indicator). Because there were more S-indicators and all indicators within the sustainability sub-index were weighted equally, each S-indicator had a smaller impact on the sustainability sub-index score than each R-indicator had on the risk sub-index score. In other words, the poor performance of a small number of S-indicators is buffered by the good performance of the rest. On the other hand, for the risk sub-index, a smaller number of indicators was considered, so each risk indicator had a larger impact on the risk sub-index score than each individual sustainability indicator had on its sub-index, comparatively. This means that even though more S-indicators underperformed in comparison to their thresholds (7 out of 34, 20.6%), the three underperforming R-indicators, out of 11 R-indicators in total, played a more significant role in the risk score (27.27%). This was coupled with a higher performance score for risk in the minimum desirable state (0.89), thus increasing the gap towards its achievement. This may be due to the type of threshold; in the case of sustainability, more ranges were used (e.g., 1-5 Likert scales, percentages) compared to the binary modalities (e.g., Yes-No, Absence-Presence) that were more dominant for the risk indicators. The next subsection provides details on potential improvement areas for the WS-WR situation of the case study by considering these evaluation results together with the analysis results.

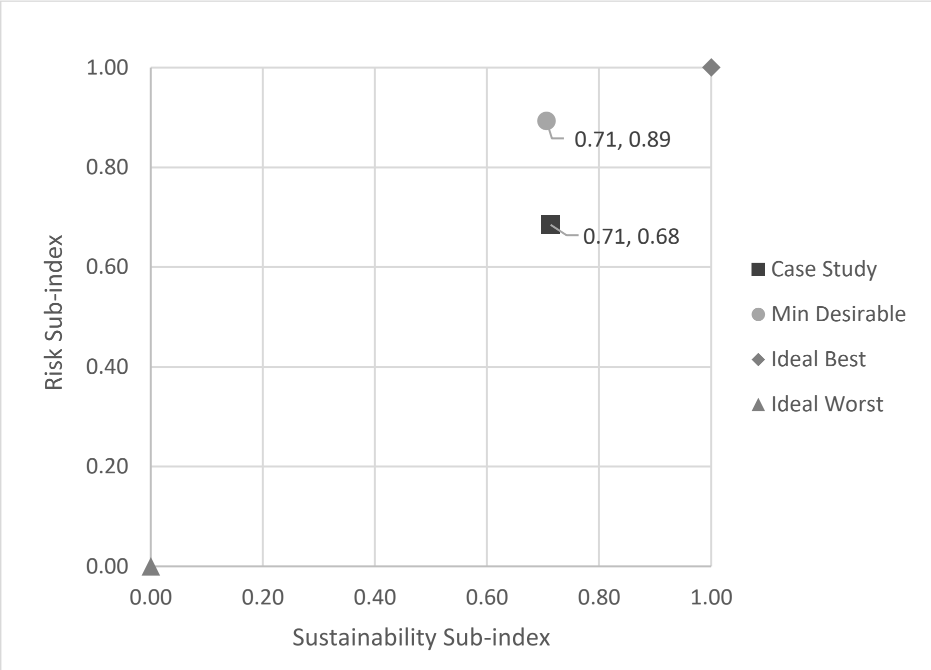

Figure 4.5 Evaluation results with respect to the fictitious 'ideal best' (1.00; 1.00) and 'ideal worst' (0.00; 0.00) scores.

4.3.3 General results for the case

The system is largely described by sustainability indicators, although the most interlinked indicators are risk-related. The evaluation showed a similar performance of risk and sustainability (0.68 and 0.71, respectively). However, based on the minimum desirable case, additional efforts are needed to reduce the risk of water scarcity.

The RSA indicates that efforts to improve the WS-WR situation in Cerrillos de Tamaya should concentrate on: (a) acquiring data regarding the community's perception and awareness about water scarcity and the controllability of its impacts; (b) reducing the poverty level to enable more and better connection to the sanitation and treatment services and to increase willingness to pay for them; (c) revising the operation and maintenance procedures towards technical improvement (e.g., installation of flowmeters in the outflow of the WWTP) and creating new jobs that could potentially support a change in the poverty level; (d) improving accessibility of surface and groundwater data for better water balance calculations, especially under a scheme of inter-basin water use; and (e) increasing the awareness of water reuse, which in turn can support its implementation as a coping measure to face a period of drought. Further data is required to propose improvements related to options such as the added value of sludge or the co-generation of energy.

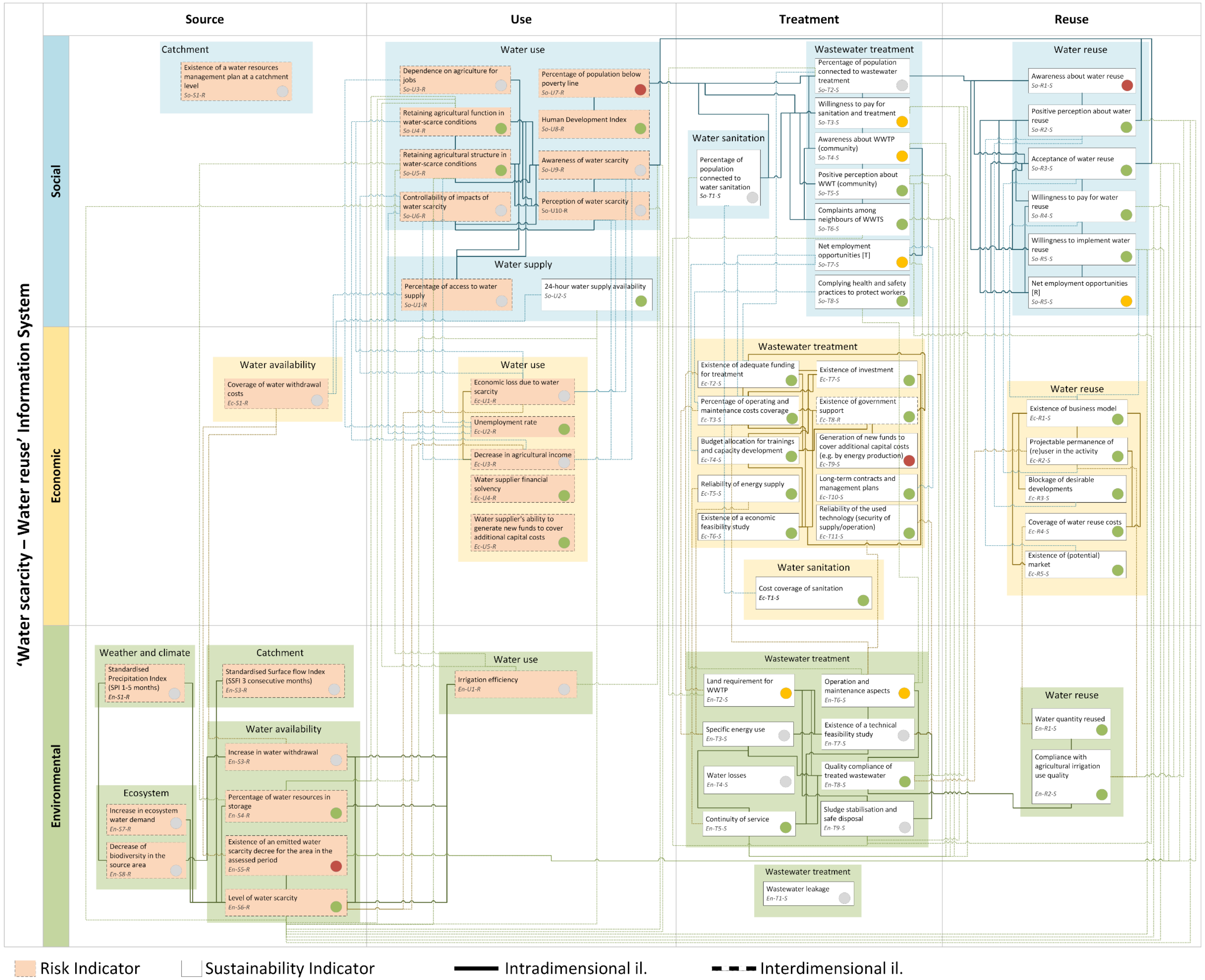

Figure 4.6 Overview of the lane-based visualisation of all layers, indicators, and interlinkages. Attributes are omitted for space reasons. Red-, yellow-, and green-coloured circles refer to the colour coding used in the evaluation (see subsection 4.3.2). Grey represents no data. For a detailed view, please access the online figure; the full list of indicators is accessible in SM-B, -D and -E. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

4.4 Discussion

The focus of the discussion is on the results of testing the analysis and evaluation phases of the RSA Framework in a case study, rather than on the analysis and evaluation of the framework itself.

4.4.1 Analysis

The main discussion points related to the analysis phase refer to (1) the interlinkage between risk of water scarcity and sustainability of water reuse, (2) issues about scales, (3) interlinkages across dimensions and their directionality, and (4) the disciplinary scope and automation.

First, from the analysis, it is possible to see that risk and sustainability indicators are not highly interlinked (11.7% of the total il.). Thus, improvement in sustainability of water reuse will not necessarily translate into reducing the risk of water scarcity or vice versa. This same conclusion was reached by Müller et al. (2022) in their example case. The testing of the RSA Framework also includes interrogating its results by questioning, e.g., What does the alignment of the reported results with the current results mean for the RSA? Does the RSA tend to lead to the same conclusion; that the risk of water scarcity and the sustainability of water reuse are minimally interlinked? Certainly, this framework has not been implemented enough times for its results to indicate a trend. However, to work toward an answer, the meaning of both concepts and how they are, in principle, interlined can be considered, such as by looking at the basic indicators referring to water scarcity: "Level of water scarcity" and "Existence of an emitted water scarcity decree for the area in the assessed period". These indicators are determined by comparing demand *versus* supply available, in this case, outflow and inflow of the reservoir (see Section 4.3.3). Thus, the water flows made available through reuse are not represented by these indicators unless they have an explicit impact on the historical levels of stored water, i.e., more water is available in storage because less is demanded. In the water scarcity quotient, demand and supply have a 1:1 relation, i.e., one litre of freshwater supplies the demand for one litre of water. However, with water reuse, that litre of water could fulfil at least two different water demands: that of the initial use and the subsequent reuse(s). For determining the risk of water scarcity, this change in the relationship might not be relevant, as the interest is focused on the existing available freshwater and the demand for it. However, the calculation should remove the water re-users from the demand, as they are not demanding freshwater but are instead reusing the demanded freshwater of someone else. For cases assessing the impact of the implementation of a water reuse measure on the level of water scarcity risk, this differentiation needs to be considered for various aspects, including the interpretation of the level of water scarcity and the hydrological modelling for scenario development. In this example, the water reuse was considered in the calculation of the environmental R-indicator "Level of water scarcity" but not for the decree-related R-indicator: the farmer was demanding less water from the reservoir because of the implemented water reuse, influencing the outflow of the reservoir used for the calculation of the "Level of water scarcity". This means that the boundaries in WS-WR situations are extremely important in determining the water balances, what the input and output are, and what can be considered as recirculated within the system; thus, the potential linkage between the risk of water scarcity and sustainability of water reuse.

Second, the score of the decree-related indicator brings into focus a discrepancy with the indicator "Level of water scarcity" regarding the understanding and measurement of water scarcity in terms of spatial scale and calculation. According to the water management authority, decrees can be emitted at the level of a catchment, commune, province, and even region (DGA 2021). This already shows a mix of hydrological and administrative scales. In this case, the decree was emitted in June 2019 for the Coquimbo Region, affecting the score of the decree-related environmental R-indicator. However, the environmental R-indicator "Level of water scarcity" was calculated for the specific case of the Recoleta reservoir (within the Coquimbo Region) based on the demand-*versus*-supply understanding of water scarcity –as it is still the source for irrigation of half of the studied agricultural field– (e.g., Müller et al. 2020). In this case, given the lack of data available to calculate the total water demand of that source, the inflow (0.659 m^3/s) and outflow (0.567 m^3/s) of the reservoir were considered as a representation of the supply and demand, respectively. These flows yield no imbalance at the time. The national regulation recommends a similar approach for reservoirs; where a situation of water scarcity can be declared if the water volume in the reservoir (i.e., the difference between inflow and outflow) is lower than 60% of the historical statistical average of the respective month (DGA 2012). For June in 2019, the accumulated volume was exactly the same as the historical average (~79% of the maximum capacity) (DGA 2019). Thus, at a reservoir level, there did not appear to be biophysical water scarcity but at a regional level, a water scarcity decree was emitted, showing a discrepancy between the biophysical and administrative views of the situation.

Third, even though the effect of water reuse on the level of water scarcity may not be explicitly addressed by the mentioned environmental indicators, their connection can be seen across dimensions. For instance, the environmental R-indicator for emitted decrees was linked to social indicators such as awareness, perception, and acceptability of both water scarcity and water reuse and the social indicators measuring the retention of agricultural structure and function. The more decrees are emitted, people can become aware of the situation of water scarcity –if they were not living the consequence already– and as a consequence of these negative impacts of water scarcity may improve their perception and acceptability of water reuse (e.g., Deh-Haghi et al. 2020). This example raises two important points related to the interlinkages between social, economic, and environmental factors and the importance of interlinkage directionality:

a) All dimensions are part of the same assessment but they can evaluate the same stimulus differently (here, the effect of water reuse on water scarcity). Therefore, attention on understanding the particular considerations and attributes associated with each indicator is needed, i.e., how it is calculated to better determine and understand the interlinkages between different dimensions.
b) Even though no directionality was established, the emission of a water scarcity decree (i.e., the underperformance of the indicator) may influence changes in the scores of the social indicators rather than the other way around. This complicates the recommendation of useful strategies to improve the performance of this indicator by improving the performance of interlinked indicators. Thus, the importance of specifying the directionality of interlinkages, already discussed by Müller et al. (2022), became evident when testing the approach. Directionality would help provide additional information for the development of targeted strategies to indirectly improve the performance of indicators by enhancing the performance of interlinked indicators following, for example, the causality rationale "If-Then" (e.g., Rubio-Martin et al. 2020). This is relevant for addressing underperforming indicators or even missing data

Finally, regarding the analysis phase in the RSA Framework, two interesting discussion points are:

a) For the multi-layer approach, collaborative multi- or interdisciplinary approaches towards the identification of endpoints and even transdisciplinary approaches for descriptors and indicators would probably enable a more accurate result, as more elements could be included. However, this could lengthen the time required for the process since communication and consensus on the inclusion of relevant aspects require proper planning and scheduling. In this case, due to time and capacity constraints, scientific literature supported the identification of these indicators and their interlinkages. Grey literature helped to determine the thresholds when possible; otherwise, they were defined subjectively, trying to align as much as possible to the preferences of the contacted stakeholders. A full stakeholder analysis (including e.g., a Social Network Analysis) would allow knowing which of the stakeholders' preferences was followed, e.g., a powerful stakeholder.
b) For the lane-based approach, a more automated process is required, as a manual identification of interlinkages is time-consuming, especially if the aim is to include interlinkages based on reported correlations. However, such matrix-based comparison approaches have been used to analyse other topics, such as policies (e.g., Papadopoulou et al. 2020), where the matrix is shared among the researchers and experts and is completed based on their disciplinary or sectoral knowledge and experience. Automation would require a detailed database and clear interlinkage criteria. For the RSA, this means that the database should contain: (1) all indicators and their attributes and (2) the list of indicators' correlation to each other, together with the source of this information for a transparent evidence-based process.

4.4.2 Evaluation

The main discussion points regarding the evaluation phase of the RSA relate to the (1) performance results, (2) data availability, (3) weighting and aggregation, and (4) the selection of the evaluation method.

First, from the evaluation, it was possible to identify the four most underperforming indicators (i.e., worst scores) as being related to the poverty level, awareness of water reuse, new funding alternatives, and the emission of a water scarcity decree. These were then identified in the lane-based matrix to check their connectivity with other indicators to guide a targeted strategy for performance improvement (Figure 4.6). This means the plan may include improvements of interlinked indicators that indirectly positively affect the performance of these particular low-scoring risk indicators.

For the case of risk, the social and environmental aspects scored poorly compared to the determined thresholds. Regarding the performance associated with the scores of the indicators, for social aspects, the main focus for improving these scores is on decreasing the social vulnerability of the area (e.g., the poverty level). For the environmental performance, improvements are more complicated, especially because the score of the indicator "Existence of an emitted water scarcity decree for the area in the assessed period" is likely to increase (worsening the performance) due to the drought affecting the region. Thus, there is no immediate action to remedy this.

From a sustainability point of view, the performance scored by social and economic indicators seemed to be of concern. The two most underperforming indicators were part of the least interlinked indicators, which means that it is unlikely that their performance will improve due to an improvement in other indicators. The social indicator “Awareness about water reuse” appears to be connected to indicators of perception, acceptance, and willingness to implement water reuse (e.g., Tang et al. 2013; Rice et al. 2016; Barnes et al. 2021), whose performances likely improve from an increased awareness rather than the other way around. This again highlights the need for the directionality of the interlinkages. Therefore, an indirect improvement of the awareness indicator’s score, i.e., by improving the performance of other indicators linked to awareness, is unlikely. This calls for a direct intervention via, e.g., awareness-raising campaigns (e.g., Massoud et al. 2018; Smith et al. 2018). From an economic perspective, improvements are required regarding the “Ability of generating new funds to cover additional capital costs” (S-indicator). Such an ability is mainly related to exploring new business or funding opportunities, which are currently external to the studied system, e.g., co-generation of energy and commercialisation of stabilised sludge as fertiliser.

Second, the risk evaluation could have been improved by better data availability. Using the most interlinked indicators ranking it was possible to estimate the impact of this missing data; missing data of highly interlinked indicators can be considered more relevant since these indicators are highly interlinked within the information system. For instance, three R-indicators that were not evaluated belong to the top ten most interlinked indicators. These are the social R-indicators of awareness, perception, and controllability of the impacts of water scarcity. This missing data contributed to the contrasting number of R- and S-indicators used in the evaluation. If the data were available, it would affect the overall RSA index score. It could be used to define performance improvement strategies based on their interlinkages with other indicators, e.g., regarding the “water use efficiency”. Likewise, having information available for the indicators interlinked to these missing-data-indicators (e.g., good performance of the indicators related to maintaining the agricultural structure and function despite water scarcity, which is linked to the “Controllability of impacts of water scarcity”) could, to an extent, indicate a good performance or guide the intervention plan despite missing data.

Third, regarding the weighting and aggregation calculations, there is a broad variety of available multi-criteria methods (e.g., Wątróbski et al. 2019). An alternative to the current weighting scheme could involve a participatory approach to determine the value of each indicator according to different stakeholders via, e.g., Analytical Hierarchy Process (AHP). However, in such participatory processes, a smaller set of indicators is recommended (seven per comparison set) (Yoon and Hwang 1995). This reduction in the number of indicators makes the evaluation less comprehensive, but it can buffer the data availability issues. For the aggregation into a final index, the use of TOPSIS corroborated the easy-to-programme and low-computational-requirements features of this method, making it more accessible (e.g., through the use of MS Excel). The modified version of this method allowed better adaptation to the case study by not having a comparison between alternatives but rather providing a comparison against specific thresholds for each indicator, using upper and lower limits to develop the ‘ideal best’ and ‘ideal worst’ cases.

Finally, the selection of the evaluation method is also an interesting discussion point, as it can be either subjective, through familiarity with the model or based on available models at hand (Hanne

1999), or based on a clear problem definition and a selection process (e.g., Wątróbski et al. 2019). These ways of selecting the evaluation method led to an apparent loop between the problem definition and description and the chosen model, where in some cases, the problem might be described according to or to fit the calculation model criteria. This loop adds a point that requires particular attention in the assessment process and reveals the importance of clearly defining the aim and investing time in understanding the situation to define the problem. Thus, the importance of the analysis phase in an assessment is key in determining how the WS-WR situation will be evaluated.

4.4.3 Overall discussion on the testing of the RSA Framework

The main general discussion points involve (1) the call for additional testing, (2) relevant outputs of an analysis grounded on a multi-layer and laned-based approach, and (3) the relevance of the scope of risk and sustainability assessments for an integrated evaluation.

In the case of Cerrillos de Tamaya, even though risk and sustainability aspects did not appear to be highly interlinked, the support offered by the water reuse measure during the water-scarce period was recognised while showing an acceptable degree of sustainability. To determine the value of this support in a comparative manner, the system representation could be modified to include other farmers using freshwater for irrigation and evaluate their maintenance of the agricultural structure and function. This would result in a comparison between non-water-reuse cases and water-reuse cases. Given that research anticipates water quantity issues in the future (Fuentes et al. 2021), other localities could implement water reuse measures, especially in coastal areas where wastewater is discharged into the ocean (around 8 m^3/s; (EH2030 2019)). The project Water Scenarios 2030 (EH2030 2019) determined that reusing the wastewater discharged into the ocean could reduce the existing water gap in the country by 10%. However, it is still challenging to determine future water scarcity risks for this case, given the available data.

The analytical approach is still in an early stage of development. Despite the suggested points of improvement and specific challenges mentioned above, the analysis results are useful to determine a preliminary level of relevance to the data that is missing, which in turn can help offer perspective on the results of the evaluation. It also provides information that strengthens the results of the evaluation to (a) design a targeted strategy that considers indirect performance improvement (e.g., improving the "Willingness to pay for sanitation and treatment" by advancing the "Continuity of service" and "Quality compliance of the treated wastewater"); (b) estimate the relevance of the data for the evaluation (e.g., missing data as in "Controllability of impacts of water scarcity"); (c) have a better understanding of the use of indicators and how they connect to the WS-WR situation via the multi-layer and lane-based diagrams; and (d) visualise results and facilitate communication with stakeholders (e.g., Rhoades et al. 2014; Voinov 2018). As such, this analysis does not intend to replace the current systems dynamics modelling approaches but rather to use them as inspiration to bridge a systems view of the WS-WR situation with an assessment of its performance. This assessment is carried out at an information level, and, thus, translates the CHANS view into the information system.

Finally, despite it being mathematically feasible to integrate risk and sustainability evaluations, there is a discrepancy with the temporal scale normally used in risk and sustainability assessments. Risk is normally assessed based on scenarios of possible or probable events and simulations, assessing one or more points in time (e.g., Veldkamp et al. 2016). In contrast, sustainability assessments (in the wastewater sector) mostly rely on snapshot approaches, assessing one point in time (Zijp et al. 2017). This discrepancy poses the decision to either address sustainability in a scenario-based manner by developing projections or simulations for the social, economic, and environmental aspects; or to address risk from an event-like snapshot point of view by determining the degree of risk-associated factors for a particular point in time, i.e., not as a probability of occurrence in the future. Due to the challenges involved in developing consistent scenarios that couple the social, economic, and environmental indicators evaluated in this case study, it was decided to narrow down the risk assessment to a snapshot mode. This meant addressing risk as an even and sustainability as an average of social, economic, and environmental aspects. Thus, the result, rather than presenting a future probability of occurrence, reflects the current state of vulnerability (water demand) and exposure (crop area) to the existing hazard (available water quantity). This decision seems appropriate from the point of view of trying to interconnect both approaches; however, it would be useful also to identify a probability-based degree of risk determined via traditional risk assessments. Overall, this demonstrated that temporal scales are a key challenge in integrating risk and sustainability assessment approaches. This challenge is probably also why attempts to integrate risk and sustainability have been unsuccessful thus far. From a conceptual perspective, these concepts seem to align (Müller et al. 2020), and even from an analytical point of view, the information could be analysed in an integrated manner (Müller et al. 2022); however, from an operational evaluative point of view, it becomes quite challenging. Thus, further development is required to couple models to project or simulate sustainability from a scenario point of view.

4.5 Conclusions

The current article tested the conceptual framework of an integrated RSA for WS-WR situations with its analytical concept in an *ex-post* manner in a case study in the locality of Cerrillos de Tamaya, Chile. Results showed an assessment largely based on sustainability indicators, signalling an acceptable degree of sustainability of the water reuse measure, with a degree of risk not reaching the minimum desired case. Overall, results indicated a low interlinkage between risk and sustainability indicators, implying that no considerable improvement in risk reduction is expected by improving water reuse sustainability, and vice versa. This result allowed reflection on the connection between water scarcity and water reuse at an indicator level; while their connection is not explicit in environmental indicators, the effects of water reuse could be recognised in the social dimension. This unexplicit connection highlights the existing differences between the approaches to assess the WS-WR topic across the different dimensions.

The main limitations of this research were data accessibility and the inherent bias of the authors in the translation process, e.g., decisions made in terms of listing indicators. However, the identification of interlinkages across indicators could help, to some extent, compensate for data gaps; participatory approaches could also buffer these gaps for evaluation. Also, the RSA Framework offered support in addressing the comprehensiveness of the WS-WR situation in an organised manner, while demonstrating the well-recognised trade-off of models and assessments between comprehensiveness and operability (making them less complicated for implementation) (Sayers et al. 2016; van Vuuren et al. 2016; Kaddoura and El Khatib 2017; Purwanto et al. 2021). Additionally, the testing of the RSA Framework allowed (1) recognition of methodological integration between risk and sustainability, especially regarding the temporal scope of scenario *versus* snapshot approaches, respectively; and (2) reflection on the incorporation of the quantity of water reuse into the concept of water scarcity (understood as the quotient between the quantity demanded and the quantity existing for supply). Overall, these methodological compromises for integration (comprehensiveness *vs* operability, scenario *vs* snapshot) mean that the RSA, as implemented in this case, does not intend to replace traditional simulation-based risk assessment with future projections.

Regarding the outlook of this work, the analysis in the RSA Framework could benefit from the specification of interlinkage directionality and automation. Directionality has resulted useful in systems dynamics modelling (e.g., Rubio-Martin et al. 2020), which could serve as inspiration for further advancing the RSA. If so, the identification of interlinkages would have to consider not only the use of the same indicator attributes or the correlation between indicators but also a causality in changes in the indicators' scores. For automation, future developments should consider developing a database of risk and sustainability indicators that includes their respective attributes and ideally also, the interlinkages. Likewise, a more automated tool could be inspired by other fields, such as management and business process modelling software.

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Chapter 5 Synthesis

This chapter aims to summarise relevant points discussed in the previous chapters that allow answering the research questions of this dissertation and interrelate crosscutting aspects synthesising important discussion and learning points. As such, it focuses on:

- Conceptual aspects that allow building the conceptual framework for an integrated RSA, and how these conceptual aspects can determine the methods involved in its operationalisation.
- Methodological aspects that support the operationalisation of the RSA Framework and crosscutting aspects that can influence the conceptual framing.
- The testing of the RSA Framework, lessons learnt and aspects that limit the conceptual and methodological predefinitions.
- Bringing these key aspects together to set the RSA Framework in the broader context of water resources management for water security under global decision-making discourses as introduced in Chapter 1.

Most of the crosscutting reflections correspond to ongoing academic discussions that are not necessarily solved or refer to aspects addressed on a case-by-case basis.

5.1 Conceptual aspects

Chapter 2 presents the core points needed to answer RQ1: How is decision-making regarding water reuse understood and supported towards reducing the risk of water scarcity sustainably – and how can it be represented in a conceptual assessment framework? These can be summarised by the structure proposed by behavioural decision-making theory and risk assessments (Müller et al. 2020). Decision-making encompasses a four-step cyclic process starting with defining a clear interest or aim, followed by framing and understanding the different components of the situation, judging the situation according to criteria that meet the interest or aim, and concluding with the choice (ibid.). In contrast, a risk assessment can follow a structure comprising an analysis phase and an evaluation that is used to structure the RSA (ibid.). A relevant point in this regard is the high complementarity of both structures. The analysis phase aims at a rather objective description of the situation that supports framing and understanding it. The evaluation phase aims at a subjective judgement of the situation based on established criteria that align with the interest or aim. Further reflection on the relevance and determining role of the aim, the objective and subjective elements within the RSA Framework (e.g., modelling tools and decision-makers preferences), and how it can relate to a broader context in water resources management are discussed throughout this chapter.

Additionally, two key conceptual aspects are crosscutting for this work, as they challenge not only building a conceptual framework but also determine the methodological operationalisation of the RSA Framework.

First is the great variety of definitions. Chapter 2 shows how this becomes especially evident for water scarcity, where despite a general common understanding, there are subtle differences between "water scarcity" and "water stress". Similar is the case of "water reuse" and "water reclamation", where reclamation relates to the concrete quality regulations that have been developed to standardise the safe reuse of water resources (European Parliament 2020). These differences influence the type of indicator and thresholds that should be included in the assessment. For instance, in the Chilean case study, the water scarcity situation was declared at a regional scale, as the regional criteria of the national resolution indicated a scarcity situation (based on Standardised Precipitation Index -SPI- and Standardised Streamflow Index -SSI-). Still, at a reservoir level, following the same resolution, no water scarcity should have been declared. It does not mean that the measurements are wrong but that they indicate different issues; in the first case representative of a drought situation and the second more related to water scarcity. If this differentiation is not clear and the metrics are used to indicate the same problem from different perspectives (in this case, water scarcity), it becomes challenging to address the request of developing comprehensive frameworks and assessments that include all of these perspectives. In other words, the problem narrows down to dealing with having two or more correct but opposing criteria, challenging a consistent integration of the different views.

Regarding risk and sustainability, there is not a great divergence in the number of definitions, but there are differences in how they are defined and operationalised by dimensions. For instance, in the case of risk, researchers focusing on vulnerability aspects consider exposure to be contained within the vulnerability dimension (e.g., Collins and Bolin 2007; Adger et al. 2009; Bennett et al. 2016). In contrast, other views present exposure as part of the hazard (e.g., Mucke et al. 2019). Finally, others present it as a separate dimension intersecting vulnerability and the hazard (e.g., Garrick and Hall 2014). In the case of sustainability, the social, economic, and environmental dimensions are broadly recognised but there are proposed additions to the triple bottom line, for instance, including institutional aspects and cultural ones (e.g., Waas et al. 2011; Soini and Birkeland 2014; Pires et al. 2017). These understandings result in differences in operationalisation and thus in the implementation. Criticism of the sustainability concept is not only related to referring to the operational dimensions but also about its definition being vague (Purvis et al. 2019). However, this has a purpose as it aims to convene different actors and build consensus, and thus a concept with a "sufficiently vague" definition may be useful (ibid.). It may be especially useful when the operationalisation occurs in an inter- or transdisciplinary setting. It is important to understand that different communities develop different terms to describe similar concepts, or the same terms may be understood and used differently across disciplines (Dewulf et al. 2007). This challenges a consistent integration and operationalisation already at the stage of determining the goal of the assessment (derived from the general understanding of what should be assessed) (Morrison-Saunders et al. 2015). Thus, it is relevant to determine a common language when developing a conceptual framework, starting by reviewing and compiling different definitions to choose the ones suitable for the framework. For the development of the RSA Framework, using "sufficiently vague" definitions allowed connecting different perspectives within each conceptual field and across them, enabling to reconcile and integrate the views of risk and sustainability to frame WS-WR situations in one conceptual framework. Furthermore, as mentioned in Chapter 2, together with common terminology, the use of conceptual maps is valuable as it supports the understanding among different disciplines and the communication with stakeholders.

The second relevant aspect that becomes evident when developing a comprehensive conceptual framework, while keeping in mind its operationalisation, is the challenge of having a generic view that simultaneously adapts to case-specific settings. Given the criticism mentioned above about the vagueness of the definition, it is possible to understand that both holism and specifications are appreciated. However, there is an apparent trade-off between a holistic concept and its operationalisation. Toumi et al. (2017) also flag this for the concept of sustainability and the challenges of its assessment. Nevertheless, as Chapter 1 introduces, the request for holistic or comprehensive frameworks that address an array of views of one situation remains. For the case of the RSA, the lesson learnt is that there are two possibilities: (1) keeping it on a generic level providing broad categories and guiding steps, or (2) taking it to a specific level by exploring all possible settings and combinations. The latter would mean implementing the conceptual framework via case studies or thought experiments to define methodological specifications that suit each possible setting where the framework could be implemented. The associated complication of such a task is why the RSA Framework is not prescriptive with the evaluation method. The optimal method suggestion would result from several tests with different methods. In turn, the selection of the method, as discussed below, is quite context-specific and dependent on the situational decision-making aim. Likewise, the RSA does not work with a defined set of indicators and rather focuses on (1) setting the conceptual background that allows characterising the WS-WR situation, and (2) guiding what general steps could be followed to determine, analyse, and evaluate these indicators on a case-by-case basis. Ultimately, this is probably the reason why such "universal", "one-size-fits-all" approaches to fulfil both the generic conceptual understanding as well as the details required for a context-specific implementation have not been developed or massively used.

5.2 Methodological aspects

From a methodological point of view, Chapter 3 addresses the main points to answer RQ2: How can a conceptual framework for assessing water reuse as sustainable water scarcity risk reduction measures be operationalised through a methodological framework? The operationalisation mainly relates to deriving, organising, and linking the required information to assess WS-WR situations (Müller et al. 2022). These are based on systems thinking and traditional indicator-based evaluation methods (ibid.). The main innovation is the proposal of an analytical concept that allows translating an initial understanding of the WS-WR situation as a CHANS into an information system that aligns with the indicator-based evaluation that will ultimately measure the performance of the WS-WR situation. This translation relies on including, in the analysis phase, the indicators to be used in the evaluation, allowing the analysis to be an instance to derive these indicators from the initial understanding of the situation (Multi-Layer approach) and also to view the linkages of the information that will be used to evaluate it (Lane-Based approach). Finally, the evaluation can be carried out using traditional methods such as MCDM methods that require appropriate consideration of the type and number of indicators, their weights and aggregation, and threshold values as evaluation criteria.

In addition to the discussion in Chapter 3, there are three main cross-cutting aspects to highlight. These relate to the derivation of indicators, the selection of the evaluation method, and the methodological integration of risk and sustainability approaches while having different conceptual origins.

First, the analytical concept proposes the idea of a structured derivation of indicators for an assessment based on a system's understanding of the situation. This is relevant because the selection of appropriate indicators is a widely discussed topic not only because of the plethora of indicators but also because of their value in actually being a good metric to represent part of the situation (Moldan et al. 2012; Morrison-Saunders et al. 2015; Zijp et al. 2017). Among several considerations for the development of the RSA Framework, there are three that stand out with regards to indicators: (1) the effect of the initial conceptualisation of the framework as the indicators are selected or derived based on the aim of the assessment, which is framed by the understanding of risk and sustainability; (2) the representativeness and accuracy of indicators, especially regarding data requirements, connecting to the trade-off of a wide application *versus* an appropriate accuracy (Ostendorf 2011); and (3) the broad pool of indicators available (e.g., Damkjaer and Taylor 2017; Benavides et al. 2019). These considerations are relevant as indicators provide information for decision-making, and ultimately, what is not measured cannot be assessed, thus, posing the question of what the optimum level of information is before falling into trying to model and measure everything. This probably corresponds to the art of balancing these three basic considerations. However, a systems visualisation to interpret the situation facilitates a common understanding that can foster an appropriate derivation of what the assessment should measure.

Second, from an evaluation perspective, a critical point that resulted in not being trivial is selecting the evaluation method. Only within the multi-criteria decision-making (MCDM) methods, there is a great variety of methods that have slight differences in their aim (e.g., ranking *versus* categorisation of alternatives) and calculation approach (weighting and aggregation) (Maiochi 2021). The selection of these methods should be facilitated by a sound conceptual framework and can be supported by selection guidelines such as the one developed by Wątróbski et al. (2019). These guidelines stress that the definition and characterisation of the problem is one of the starting points for choosing the appropriate decision support method (Guitouni and Martel 1998; Wątróbski et al. 2019). Here, the conceptual aspects are highly relevant as they frame the user's understanding of the problem at hand, in this case, the understanding of water scarcity as a risk and the sustainability of water reuse. However, despite such supporting frameworks, a loop between the problem description and the method selection appears. On the one side, the problem can be generally defined and then methods are screened to find one or a set of suitable ones. On the other side, methods might be selected based on previous knowledge or affinity of the user, and then the problem is defined to fit the method’s criteria (Hanne 1999; Maiochi 2021). Thus, methods that are familiar or available to the user can ultimately define the conceptualisation of the decision-making problem, shaping the aim of the assessment. For instance, focusing on scenario-based modelling for the case of risk and snapshot approaches for the case of sustainability. This connects to the third and last crosscutting aspect.

Third, the incompatibility of temporal scales became evident, i.e., trying to reconcile the projection view of risk assessment methods with the snapshot view of sustainability assessments. Conceptually, both should have scenario-based thinking, especially given the future-looking view of sustainability; however, sustainability assessments rely primarily on a snapshot view of the situation (Zijp et al. 2017). It is possible to infer that the reason behind it is the difficulty of simultaneously addressing the social, economic, and environmental dimensions via coupled projections and models to develop one or multiple scenarios. It probably becomes particularly challenging for indicator-based assessments where the indicator selection, in addition to the criteria mentioned above, needs to include compatibility across dimensions in terms of temporal and spatial scale. Thus, despite a clear conceptual understanding of sustainability, focused on long-term solutions, methodological limitations can restring its operationalisation and integration with other perspectives, such as risk.

5.3 Testing aspects

The discussion section in Chapter 4 presents several points regarding the implantation of the RSA Framework and RQ3: What are the findings from testing the framework in a case study – and what can be incorporated into the framework? The main points to reflect on are the conceptual framing for the derivation of indicators as well as the understanding of their meaning and the challenges for the integration of scenario-based and snapshot methods (mentioned in section 5.2). On the one hand, for the RSA, it is of high importance to reflect on the understanding of water scarcity indicators, and how they are calculated to correctly establish a link with water reuse and allow measuring the effect of water reuse on water scarcity. Similar is the need of clarifying how indicators measure the same stimulus across dimensions, for instance, how the effect of water reuse on water scarcity is evaluated from a social perspective (e.g., changes in perception of water scarcity) and an environmental perspective (e.g., water availability indicators). On the other hand, the points mentioned above about the selection and scope of the evaluation methods were critical in the testing of the RSA Framework. Overall, the findings regarding the conceptual framing and understanding of indicators suggest that the RSA Framework could benefit from including: interlinkage directionality, system dynamics modelling (e.g., CLD, SFD) for the ML approach, an established database of indicators, and the automation of the interlinkages analysis in the LB approach. Regarding the methodological challenges, the RSA Framework could profit from further advancements in using scenarios for sustainability evaluation for better coupling with risk evaluation methods.

Additional aspects to the ones mentioned above mainly refer to operational limitations. First, the inherent limitation of properly representing the situation as it was not possible to be personally present on site and talk to the different types of stakeholders. This could increase the risk of missing relevant elements of the system and evaluation information (e.g., social indicators' scores) and criteria (e.g., establishing a desired target threshold for specific indicators). As such, the work relied mainly on secondary data retrieved from public reports and the websites of Chilean authorities. Despite this, it was possible to notice a divergence between the data and conceptual considerations, such as the level of water scarcity mentioned above. Likewise, indicators covered different temporal scales, for instance, the score of the social indicator "Human Development Index" corresponding to the year 2015. In contrast, most of the other data could be retrieved for 2019. This evidences the challenge of counting with data that can describe the same WS-WR situation (in space and time) from three different perspectives, social, economic, and environmental.

Second, a crosscutting aspect related to the methodological points mentioned above is the possibility of using participatory methods. Transdisciplinary research and participation of stakeholders has gained importance for the design and implementation of sustainable solutions, especially for the acceptance of water reuse (Moser 2016; Brombal et al. 2018). Relevant stakeholders may participate not only in providing information for the target state (threshold values) but also in assigning the indicators' weighting values used by the calculation method. Such is the case with the Analytical Hierarchy Process (AHP). As presented in Chapter 4, this approach offers the possibility of buffering data availability issues or methodological gaps by limiting the amount of data that can be processed in a participatory manner. This reinforces the argument of the conceptual and methodological implications of choosing an evaluation method.

Third, the implementation of the framework provided evidence of the need for automating the analysis as well as the relevance of the indicators' definition in terms of their attributes and the information they provide. Likewise, it would be useful to count on a repository of social, economic, and environmental indicators of the risk of water scarcity and the sustainability of water reuse.

Ultimately, the testing phase allowed recognising the differences between the three steps of the research approach: conceptual, methodological, and testing (empirical). Each one faces its challenges and frames the scope for the development of the next. Still, ultimately there is some degree of iteration as factual limitations (e.g., method and data availability) in the following step imply adjustments of the previous one for a proper alignment (e.g., adjusting the risk evaluation to a snapshot approach).

5.4 Placing the RSA Framework in a broader context

This section refers back to the overarching topics introduced in Chapter 1, relating the RSA Framework to water security, general risk and sustainability discourses, and other approaches relevant to water management. It also briefly outlines the overall achievements of the RSA Framework.

Regarding water security, the design of the RSA Framework particularly tackles water quantity issues and their solutions. Among those solutions, water reuse is only one of the possible alternatives. Given the generic character of the framework, it would be possible to adapt it to other solution measures (e.g., desalination or water harvesting) and include quality and accessibility aspects to address water security fully. The general steps of the framework, namely, the definition of the aim, analysis (interpretation as a system, translation into an information system, derivation of indicators and analysis of interlinkages), and evaluation would remain valid, requiring small adjustments. For instance, defining an aim that includes assessment of quality and accessibility; interpreting the situation and delineating the CHANS (including polluting points or distant wells used to fetch water); and deriving appropriate quality and accessibility indicators (e.g., physicochemical characteristics of the water -pH, temperature, BOD, etc.-, distance to sourcing well, number of wells in the area).

Regarding the general view on risk and sustainability discourses and global agendas, it is possible to confirm that these discourses can be reconciled conceptually for the case of WS-WR situations. However, a full integration requires further methodological advances, especially in reconciling the time-scale view. Overall, the RSA Framework corresponds to the management instrument dimension of IWRM (see Table 1.1) to support decision-makers in reducing disaster damage related to the disruption of basic services such as water supply (target -d- of the Sendai Framework - Figure 1.1). By aligning with the Sendai Framework, it relates to SDG 11.b of the 2030 Agenda for Sustainable Development. It also relates to SDG 6 by supporting the implementation of sustainable water reuse measures to reduce the number of people affected by water scarcity. The RSA also provides a structured approach to identifying information linkages across risk and sustainability discourses. Despite showing rather low number of interlinkages in the theoretical example (Chapter 3 and the empirical testing (Chapter 4), it was possible to identify that the main connection is on a social level. Furthermore, the structured combination of risk and sustainability discourses offered by the RSA Framework aims at bridging science and (decision-) policy-making.

The connection of the RSA Framework with water resources management approaches such as IWRM and Nexus thinking relies on (a) a view of wastewater as a resource instead of waste and (b) the use of a system's thinking to interpret the situation and analyse interlinkages between the different types of indicators. Ultimately, the RSA Framework allows reflecting on:

- the decision-making process and the relevance of clearly defining an aim and investing time in the analysis.
- the data and information used for decision-making. By starting from a systems view and placing the question: What information is necessary to assess the risk of water scarcity and sustainability of water reuse?
- the inherent biases of indicator-based assessments, widely used to support decision-making, and the complexity but usefulness of interpreting the situation as a system. Thus, the RSA Framework does not intend to replace either approach but rather offers a way of bridging both views at an information level (Figure 5.1).

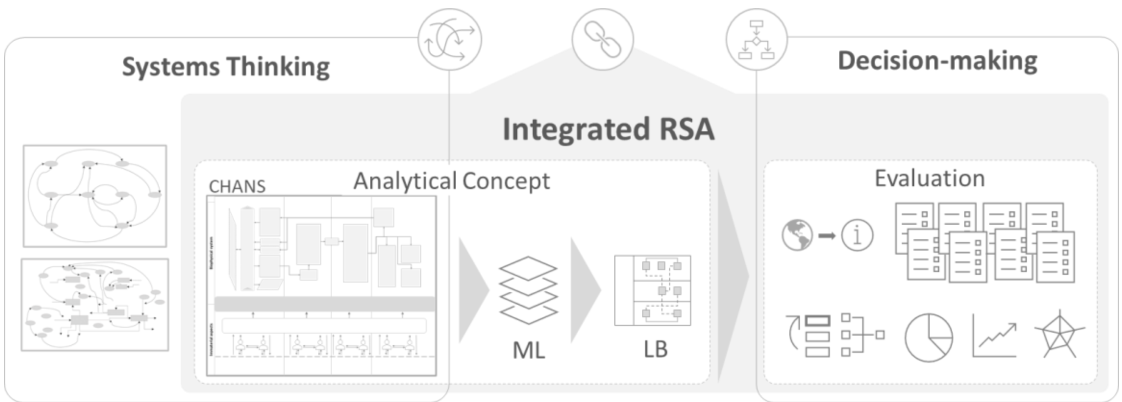

Figure 5.1: Integrated RSA to bridge a systems understanding of WS-WR situations for decision-making. CHANS: Coupled Human and Natural System, LB: Lane-Based approach, ML: Multi-Layer approach, RSA: Risk and Sustainability Assessment.

5.5 Chapter References

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Chapter 6 Conclusions and Outlook

Water security is a topic of global concern. Consequently, it is crucial to adequately manage the quantity, quality, and accessibility of water resources — this research centred on quantity issues despite the relevance of all three aspects of water resources management. The specific focus was on facing water scarcity via the implementation of water reuse measures, as it is estimated that the number of WS-WR situations will increase in the coming years. Therefore, this research aimed at supporting decision-making in these situations by providing new ideas for an integrated assessment of the risk of water scarcity and the sustainability of water reuse. This aim involves the following objectives: (A) to develop a conceptual assessment framework to support decision-making concerning sustainable water reuse in regions facing the risk of water scarcity; (B) to advance the conceptual framework interrelating existing risk and sustainability assessment methodologies and indicators in the context of decision support; and (C) to test the framework using a case study in Latin America. Three research questions (RQ1, RQ2, and RQ3) guided the work to achieve the objectives (A, B and C, respectively). Chapters 2 to 4 of this dissertation address all objectives and the concluding remarks to each RQ are as follows:

RQ1. How is decision-making regarding water reuse understood and supported towards reducing the risk of water scarcity sustainably – and how can it be represented in a conceptual assessment framework?

- Decision-making in WS-WR situations can be understood as a four-step cyclic process comprising: (1) the definition of the interest or aim, (2) the framing or decomposing of the situation to understand it, (3) the evaluation of the aspects of interest, and (4) the choice.
- The conceptual RSA framework addresses this process via an analysis (for the framing and decomposing) and an evaluation (for the evaluation step).

RQ2. How can a conceptual framework for assessing water reuse as sustainable water scarcity risk reduction measures be operationalised through a methodological framework?

- The operationalisation of the RSA conceptual framework focuses on the analysis and evaluation phases and relies on: (a) a systems understanding of the situation – as a CHANS –; and (b) the role of information, more specifically, indicators.
- The methodological aspects to operationalise the analysis focus on translating the conceptual understanding of the situation (as a CHANS) into an indicator-based information system for its evaluation.
- The operationalisation of the evaluation relies on the use of indicators, their weighting and aggregation, and their comparison with established threshold values to allow choosing among different alternatives as well as comparing the current status of one alternative with its ideal performance.

RQ3. What are the findings from testing the framework in a case study – and what can be incorporated into the framework?

- Beyond the specific findings for the cases study that suggest particular recommendations, the general findings of the case study test include: (1) the influence of the conceptualisation behind the indicators and their use and meaning across sustainability dimensions, which resulted in the identification of a low degree of interlinkage between the risk of water scarcity and the sustainability of water reuse; and (2) the methodological challenges for the integration of risk and sustainability evaluation.
- The RSA framework could benefit from (a) the inclusion of interlinkage directionality; (b) existing system dynamics modelling approaches (e.g., CLD, SFD) for the derivation of *endpoints*, *descriptors* and *indicators* (ML approach); (c) an established database of indicators; (d) the automation of the interlinkages analysis (LB approach) via a tool(s) that connected to the indicators' database; (d) further advancements in the use of scenarios for sustainability evaluation for better coupling with risk evaluation methods.

In addition to the concluding remarks for the research questions, other statements can be derived from this research. The development of the conceptual framework provides evidence (a) for a conceptual integration of risk and sustainability discourses under one decision support framework for the case of WS-WR situations, and (b) that a system thinking approach can help interpret the situation to structure the relevant elements that need to be considered in the assessment.

From a methodological point of view, the RSA framework (a) highlights the relevance of indicators as a means of representing the situation; (b) allows tackling the challenge of interlinking social, economic, environmental dimensions by placing them on the same level, the information level; and (c) benefits from different disciplines by using a variety of conceptual maps to visualise the understanding of the WS-WR situation (based on systems thinking), the derivation indicators (based on multi-layer networks), the analysis of their interlinkages and their evaluation (based on BPMN).

The testing results of the RSA framework evidence about (a) gaps between the conceptualisation of water scarcity and water reuse and their considerations at an indicator level, where water scarcity environmental indicators do not necessarily (and explicitly) include water reuse in their balance equation, whereas social indicators (e.g., water scarcity perception) do reflect the effects of water reuse; and (b) the current inability of the RSA of replacing traditional simulation-based risk assessment with future projections due to the snapshot focus of sustainability assessments.

Overall, general concluding remarks that complement the answers to the RQs can be summarised as: (a) the existence of a consistent alignment of risk and sustainability discourses for the case of WS-WR situations; (b) the need for water scarcity indicators to explicitly define and account for the quantity of water being reused based on clearly system's boundaries; and (c) the possibility of the RSA framework to bridge a system thinking view with a traditional assessment-based decision-making view (i.e., Figure 5.1).

The main limitations of this research are (1) the current time-intensive character of an analysis carried out manually; (2) the inherent biases of the people involved in performing an assessment, mainly related to natural and engineering sciences; (3) data accessibility and time constraints to test the framework in multiple case studies; and (4) the change of the risk view from scenario-based to snapshot to enable a joint assessment with sustainability.

Finally, all three objectives of this thesis were achieved, developing the integrated RSA framework for decision support in WS-WR situations. Accordingly, the research questions were addressed and answered under the specific scope to develop the RSA framework; other answers may arise under a different framing. Further distinctions to the answer of the RQs could be drawn by additional testing, e.g., in an *ex-ante* manner or comparison of multiple alternatives, as well as repeating the assessment time after implementing the chosen measures to compare results. Future work should also focus on advancing the automation of the analysis through the development of software tools and expanding the scope of the RSA to include water quality and accessibility aspects to address water security as a whole.

Annexes

Annex A - Literature review: Found records

Supplementary material (S1) of the scientific publication in Chapter 3.

Table A-1: List of records related to water scarcity risk (vulnerability) assessments.

#	Authors	Title
1	Falkenmark et al. (1989)	Macro-scale water scarcity requires micro-scale approaches: Aspects of vulnerability in semi-arid development
2	Falkenmark (1992)	Water scarcity and population growth: a spiralling risk
3	Giansante et al. (2002)	Institutional adaptation to changing risk of water scarcity in the Lower Guadalquivir Basin
4	Collins and Bolin (2007)	Characterizing vulnerability to water scarcity: The case of a groundwater-dependent, rapidly urbanizing region
5	Iglesias et al. (2007)	Challenges to manage the risk of water scarcity and climate change in the Mediterranean
6	Qin et al. (2011)	Ecological risk assessment for Water scarcity in Chinas Yellow River Delta Wetland
7	Martin-Carrasco et al. (2013)	Diagnosing Causes of Water Scarcity in Complex Water Resources Systems and Identifying Risk Management Actions
8	Huynh and Resurreccion (2014)	Women's differentiated vulnerability and adaptations to climate-related agricultural water scarcity in rural Central Vietnam
9	Abedin et al. (2014)	Community Perception and Adaptation to Safe Drinking Water Scarcity: Salinity, Arsenic, and Drought Risks in Coastal Bangladesh
10	Schyns et al. (2015)	Mitigating the risk of extreme water scarcity and dependency: The case of Jordan
11	Gain and Giupponi (2015)	A dynamic assessment of water scarcity risk in the Lower Brahmaputra River Basin: An integrated approach
12	Zheng et al. (2016)	The vulnerability of thermoelectric power generation to water scarcity in China: Current status and future scenarios for power planning and climate change
13	Costa et al. (2016)	Modern viticulture in southern Europe: Vulnerabilities and strategies for adaptation to water scarcity
14	Eakin et al. (2016)	Adapting to risk and perpetuating poverty: Household's strategies for managing flood risk and water scarcity in Mexico City
15	Veldkamp et al. (2016)	Towards a global water scarcity risk assessment framework: Incorporation of probability distributions and hydro-climatic variability
16	Brauman et al. (2016)	Water depletion: An improved metric for incorporating seasonal and dry-year water scarcity into water risk assessments
17	Meyer et al. (2016)	Hedging the financial risk from water scarcity for Great Lakes shipping
18	Pereira et al. (2017)	Human pharmaceuticals in Portuguese rivers: The impact of water scarcity in the environmental risk
19	Vinke et al. (2017)	Climatic risks and impacts in South Asia: extremes of water scarcity and excess
20	Zhang et al. (2017)	Risk analysis of water scarcity in artificial woodlands of semi-arid and arid China
21	Mahafza et al. (2017)	The role of proximity in problem identification: Risk of water scarcity in Texas
22	Qu et al. (2018)	Virtual Water Scarcity Risk to the Global Trade System
23	Fitton et al. (2019)	The vulnerabilities of agricultural land and food production to future water scarcity

#	Authors	Title
24	Del et al. (2019)	Enabling adaptation to water scarcity: Identifying and managing root disease risks associated with reducing irrigation inputs in greenhouse crop production – A case study in poinsettia
25	Zhao et al. (2019)	Virtual water scarcity risk to global trade under climate change
26	Wang et al. (2019)	Water scarcity risks mitigated or aggravated by the inter-regional electricity transmission across China

Table A-2: List of records related to water reuse sustainability assessments.

#	Authors	Title
1	Kennedy and Tsuchihashi (2005)	Is water reuse sustainable? Factors affecting its sustainability
2	Carr et al. (2010)	Water reuse for irrigated agriculture in Jordan: Challenges of soil sustainability and the role of management strategies
3	Majamaa et al. (2010)	Industrial water reuse with integrated membrane system increases the sustainability of the chemical manufacturing
4	Alves et al. (2011)	Water reuse projects - Technical and economic sustainability
5	Upadhyaya and Moore (2012)	Sustainability indicators for wastewater reuse systems and their application to two small systems in Rural Victoria, Australia
6	Corwin (2012)	Field-scale monitoring of the long-term impact and sustainability of drainage water reuse on the west side of California's San Joaquin Valley
7	Zhang et al. (2014)	Seeking sustainability: Multi-objective evolutionary optimization for urban wastewater reuse in China
8	Akhoundi and Nazif (2018)	Sustainability assessment of wastewater reuse alternatives using the evidential reasoning approach
9	Opher et al. (2019)	Comparative life cycle sustainability assessment of urban water reuse at various centralization scales
10	Ormerod (2019)	Toilet power: Potable water reuse and the situated meaning of sustainability in the southwestern United States
11	Rezaei et al. (2019)	A multi-criteria sustainability assessment of water reuse applications: a case study in Lakeland, Florida

Annex B - Example list of endpoints, descriptors, indicators, and attributes

Supplementary material (S2) of the scientific publication in Chapter 3.

Table B-1: List of example endpoints, descriptors, indicators, and attributes for a generic WS-WR situation. Example descriptors for the respective endpoint were only listed for found indicators, as the descriptors are site-specific. Risk indicators (R) retrieved from Collins and Bolin (2007) and Veldkamp et al. (2016); and sustainability indicators (S) retrieved from Upadhyaya and Moore (2012) – in this case some indicators are repeated, as the treatment and reuse stages are separated. Attributes were derived from the information provided in the references for the indicators or assumed to be required in case of no further description.

Category	Endpoint [a]	Dimension	Descriptor [b]	Indicator [c]	Attribute [d]	Type of indicator
SOURCE	**Input of water resources**	-	-	-	-	-
	Output of water resources	-	-	-	-	-
	Water in river basin	-	-	-	-	-
	Discharged water resources	-	-	-	-	-
	Available surface water	-	-	-	-	-
	Available groundwater	Environmental	Water resources available for human use	Water crowding index	Daily runoff Water province area Time slice (e.g., 30 yr) Return period Climate change projection Total population	R
			Groundwater resources for withdrawal	Number of exempt wells without access to basin-fill aquifer	Number of exempt wells without access to basin-fill aquifer	R
				Well spacing	Well spacing	R

Category	Endpoint [a]	Dimension	Descriptor [b]	Indicator [c]	Attribute [d]	Type of indicator
USE	**Water resources supplied**	Social	Drinking water supply	Proportion of housing units within municipal water provider service area	Housing units within municipal water Total number of housing units	R
				Proportion of housing units within private water provider service area	Housing units within private water provider service area Total number of housing units	R
				Proportion of housing units with exempt wells	Housing units with exempt wells Total number of housing units	R
	Water demand for domestic and municipal use	Social	Water resources demanded for domestic use	Seasonal/recreational housing units	Seasonal/recreational housing units	R
		Social	Social vulnerability	Total housing units	Total number of housing units	R
				Number of female-headed households	Number of female-headed households	R
				Number of people < age 18	Number of people < age 18	R
				Number of people > age 64	Number of people > age 64	R
		Economic	Economic vulnerability	Renter occupied housing units	Renter occupied housing units	R
				Mean housing unit value	Total housing unit value Total number of housing units	R
	Water resources required for industrial use	-	-	-	-	-
	Water resources required for agricultural use	-	-	-	-	-

Category	Endpoint [a]	Dimension	Descriptor [b]	Indicator [c]	Attribute [d]	Type of indicator
TREATMENT	**Wastewater transported to WWTP**	-	-	-	-	-
	Wastewater in WWTP	-	-	-	-	-
	Wastewater treatment operation and maintenance	Social	Workers' health and security measures	Capacity development for engineers	Hours of professional development per triennium	S
				Operators' training based on nationally accredited Water Industry Training Package	Satisfactory complying with nationally accredited Water Industry Training Package	S
		Economic	Economic feasibility	Benefit–cost ratio	Benefits quantification Costs quantification	S
				Ongoing benefits (to user and society at large)	Benefits to broader community Operational costs	S
		Environmental	Compliance with standards	Treatment of wastewater (comply with EPA guidelines for respective beneficial use of water)	*E. coli* (org/100 ml) Suspended Solids (mg/l) Biochemical/Biological Oxygen Demand (mg/l) Turbidity (NTU) Nitrate (mg/l) Ammonia (mg/l) pH	S
	Sludge production	-	-	-	-	-
	Biogas production	-	-	-	-	-
	Energy generation	-	-	-	-	-

Category	Endpoint [a]	Dimension	Descriptor [b]	Indicator [c]	Attribute [d]	Type of indicator
REUSE	**Treated wastewater for human reuse**	Social	Awareness of water reuse	Education and awareness programme	Existence of education and awareness programme	S
		Social	Perception and acceptance of water reuse	Cases of gastrointestinal disease reported	Cases of gastrointestinal disease reported	S
				Aesthetics (colour, odour, etc.)	Site condition and general observation. Colour Odour	S
				Complaint reported to the authority	Number of complaints reported to the authority	S
				Consumers' involvement in decision making	Level of involvement (decisive, suggestive, advisory, informative, not involved)	S
		Economic	Economic feasibility	Benefit–cost ratio	Benefits Costs	S
				Ongoing benefits (to user and society at large)	Level of benefits (positive or negative)	S
		Environmental	Treated wastewater for reuse in agriculture	Quantity of wastewater reused	Quantity of wastewater reused Total treated wastewater	S
				Source reduction (wherever other reuse options are not feasible)		S
				Energy consumption for reuse component	Quantity of wastewater reused Pumping efficiency	S
	Treated wastewater (TWW) for basin recharge	Environmental	Treated wastewater for basin recharge	Monitoring water table and management plan for changed condition	Years of water table monitoring (>10 y, 5-10, 2-5, 1-2, <1 years)	S

Category	Endpoint [a]	Dimension	Descriptor [b]	Indicator [c]	Attribute [d]	Type of indicator
					Existence of management plan for changed condition	
				Incident of un-seasonal flow into the waterway	Number of incidence per year (0, 1, >1-5, >5-10, >10 incidence)	S
				Restoration of environmental flow	Annual value of restoration of environmental flow	S
		Environmental	Quality of treated wastewater for basin recharge	*E. coli*	*E. coli* (counts/100ml) level of compliance (>90%, 80-90%, 60-80%,50-60%)	S
				Suspended solids (SS)	SS (mg/l) level of compliance (>90%, 80-90%, 60-80%,50-60%)	S
				Biochemical/Biological Oxygen Demand (BOD)	BOD (mg/l) level of compliance (>90%, 80-90%, 60-80%,50-60%)	S
				Heavy metal toxicants e.g., Fe, Pb, Hg, Ni, Cd (should meet the background concentration of the groundwater or drinking water quality guidelines whichever is less)	Heavy metal toxicants e.g., Fe, Pb, Hg, Ni, Cd (should meet the background concentration of the groundwater or drinking water quality guidelines whichever is less) (mg/l) level of compliance (>90%, 80-90%, 60-80%,50-60%)	S
				Salinity level	Measured salinity level Original salinity level	S
		Environmental	Ecosystem-related aspects	Habitat restoration	Contribution to habitat restoration (Annual value)	S
				Management plan for controlling disease vectors	Criteria should be determined after monitoring is started and data is available.	S

Category	Endpoint [a]	Dimension	Descriptor [b]	Indicator [c]	Attribute [d]	Type of indicator
	Sludge use	Environmental	Risk of soil contamination	Management plan for dealing with changing soil quality (salinity, toxicants, nutrients, boron concentration, pathogens presence in top layer)	Criteria should be established once monitoring is done, and data is available.	S
				Provision of biosolid use and management plan for excessive biosolid	Criteria should be established once monitoring is done, and data is available.	S
				Quality of biosolid (comply with EPA guidelines)	Criteria should be established once monitoring is done, and data is available.	S

[a] Proposed endpoints (c.f. Winz et al., 2009; Yazdandoost et al., 2020) for a generic WS-WR situation.
[b] Example descriptors for the respective endpoint and indicator. Where no indicator was found, no descriptor was proposed, as the descriptors are site-specific.
[c] Indicators found in literature. Risk indicators (R) retrieved from Collins and Bolin (2007) and Veldkamp et al. (2016). Sustainability indicators (S) retrieved from Updhyaya and Moore (2012) – in this case some indicators are repeated, as the treatment and reuse stages are separated.
[d] Attributes derived from the information provided in the references for the indicators or assumed to be required in case of no further description.

Annex C - Technique for Order Preference by Similarly to Ideal Solution (TOPSIS)

Supplementary material (SM-A) of the scientific publication in Chapter 4.

The TOPSIS method uses a distance-to-target approach that calculates the distance of each point (or alternative) to the best and worst target scores (ideal best and ideal worst, respectively) [1]. An aggregated index determined by the relative closeness to the best target represents the overall performance. A modified version of this method addresses rank reversal issues resulting from adding and removing alternatives [e.g., 2–5]. In the modified version, the normalisation and identification of the best and worst ideals are independent of the considered alternatives, resulting in an aggregated index that can be related to an absolute approach [3].

The calculation includes classifying each indicator as either 'benefit' or 'cost'. For 'benefit' indicators, the maximum data score (upper limit) is the ideal best, and the minimum data score (lower limit) is the ideal worst; the opposite is true for 'cost' indicators [6]. Here, a full compliance with the threshold values represents the ideal best target score for each indicator (see Table D2 in SM-D).

The calculations are guided by García-Cascales and Lamata [3] and Aires and Ferreira [7] as follows:

1. Defining the 'ideal best' and 'ideal worst' subdomain scores (D) for each indicator:

$$D = [d_j]_{2xn},\ d_j \in \mathbb{R} \qquad \text{Equation 1}$$

Where, d_{1j} is the minimum feasible score of D_j and d_{2j} is the maximum feasible score of D_j. For each indicator, based on its domain of scores and 'benefit' or 'cost' designation, the 'ideal best' alternative contains the best feasible score, and the 'ideal worst' alternative contains the worst feasible score. These scores can be determined by decision-makers, experts, or other involved stakeholders via participatory means, e.g., workshops, focus groups [7]. In this case, these scores were taken from literature or based on the interview with the local stakeholder. These two 'ideal' alternatives are introduced to the decision matrix with the aim of establishing the indicators' maximum and minimum values. Evaluating these 'ideal alternatives' alongside the real alternative(s) establishes the fictitious cases of a best-case scenario ('ideal best'), where all indicators perform with the best score, and a worst-case scenario ('ideal worst'), where all indicators perform with the worst score. Thus, the performance of the real alternative(s) moves between these two fictitious cases.

2. Normalising the data scores:

$$r_{ij} = \frac{x_{ij}-d_{1j}}{d_{2j}-d_{1j}},\ i = 1,2,\ldots,m,\ j = 1,2,\ldots,n \quad if\ j \in B \quad \text{Equation 2}$$

$$r_{ij} = \frac{d_{2j}-x_{ij}}{d_{2j}-d_{1j}},\ i = 1,2,\ldots,m,\ j = 1,2,\ldots,n \quad if\ j \in C \quad \text{Equation 3}$$

Where, r_{ij} is the normalised indicator data value for the ith alternative and jth indicator, x_{ij} is the non-normalised indicator data value, B represents 'benefit' indicators, C and represents 'cost' indicators. This replaces the vector normalisation from the traditional algorithm and prevents the normalised data values from being dependent on the indicator data values of the real alternatives [2,7]. Here, the 'ideal best' alternative will have a value of

1.00, the 'ideal worst' alternative will have a value of 0.00, and all real alternatives will fall between 0.00 and 1.00.

3. Calculating the weighted normalised scores:

$$v_{ij} = w_j r_{ij},\ i = 1, \dots, m;\quad j = 1, \dots, n \qquad \text{Equation 4}$$

Where, v_{ij} is the weighted normalised value and w_j is the weight of the jth indicator.

4. Identifying the positive and negative ideals:

$$A^* = \{v_1{}^*, v_2{}^*, \dots, v_j{}^*, \dots v_n{}^*\} = \left\{\left(\max_i v_{ij} \,\middle|\, j \in B\right), \left(\min_i v_{ij} \,\middle|\, j \in C\right) \,\middle|\, i = 1, \dots, m\right\} \qquad \text{Equation 5}$$

$$A^- = \{v_1{}^-, v_2{}^-, \dots, v_j{}^-, \dots v_n{}^-\} = \left\{\left(\min_i v_{ij} \,\middle|\, j \in B\right), \left(\max_i v_{ij} \,\middle|\, j \in C\right) \,\middle|\, i = 1, \dots, m\right\} \qquad \text{Equation 6}$$

Where, A^* is the positive-ideal solution, A^- is the negative-ideal solution, $v_j{}^*$ represents the best possible value for indicator j, $v_j{}^-$ represents the worst possible value for indicator j, for both 'benefit' (B) and 'cost' indicators (C).

The 'ideal best' alternative will coincide with the positive-ideal solution, and the 'ideal worst' alternative will coincide with the negative-ideal solution. Thus, the positive-ideal and negative-ideal are independent of the real alternatives [3].

5. Calculating the separation measures:

$$S_i{}^* = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j{}^*)^2},\ i = 1, \dots, m \qquad \text{Equation 7}$$

$$S_i{}^- = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j{}^-)^2},\ i = 1, \dots, m \qquad \text{Equation 8}$$

Where, $S_i{}^*$ is the distance of the ith alternative to the positive-ideal solution and $S_i{}^-$ is its distance to the negative-ideal solution.

6. Calculating the similarities to the positive-ideal:

$$P_i{}^* = \frac{S_i{}^-}{S_i{}^* + S_i{}^-},\ i = 1, \dots, m \qquad \text{Equation 9}$$

Where, the final index, $P_i{}^*$, is the relative closeness of the ith alternative to the positive-ideal solution. Following the rationale of the normalisation, $P_i{}^*$=1 for the positive-ideal solution and $P_i{}^*$=0 for the negative-ideal solution.

As no alternatives were compared, no ranking was considered. Otherwise, alternatives would be ranked in a descending order of preference from highest to lowest $P_i{}^*$ score.

References

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TOPSIS results

Table C-1 Basic information

Total Number of Indicators	45

Sustainability	34
Social - Sustainability	13
Economic - Sustainability	15
Environmental - Sustainability	6

Risk	11
Social - Risk	4
Economic - Risk	4
Environmental - Risk	3

Symbol	Meaning
A*	Positive-ideal solution (PIS)
A-	Negative-ideal solution (NIS)
Si*	Distance from the positive-ideal solution
Si-	Distance from the negative-ideal solution
Pi*	Relative closeness to the positive-ideal solution
A*_S	Positive-ideal solution (PIS) for sustainability
A-_S	Negative-ideal solution (NIS) for sustainability
Si*_S	Distance from the positive-ideal solution for sustainability
Si-_S	Distance from the negative-ideal solution for sustainability
Pi*_S	Relative closeness to the positive-ideal solution for sustainability
A*_R	Positive-ideal solution (PIS) for risk
A-_R	Negative-ideal solution (NIS) for risk
Si*_R	Distance from the positive-ideal solution for risk
Si-_R	Distance from the negative-ideal solution for risk
Pi*_R	Relative closeness to the positive-ideal solution for risk

Table C-2 Sustainability indicators

Dimension	ID	Indicator	Unit/Scale	Minimum Desirable Value	Lower Limit	Upper Limit	Ideal Worst	Ideal Best	Cost/ Benefit	Case Study Data Value	Weight
Social - Sustainability	So-U2-S	24-hour water supply availability	Yes(2)/No(1)	2	1	2	1	2	B	2	0.013
	So-T3-S	Willingness to pay for sanitation and treatment	1-5 scale	4	1	5	1	5	B	3	0.013
	So-T4-S	Awareness about WWTP (community)	1-5 scale	4	1	5	1	5	B	3	0.013
	So-T5-S	Positive perception about WWT (community)	1-5 scale	4	1	5	1	5	B	4	0.013
	So-T6-S	Complaints among neighbours of WWTS	Yes(2)/No(1)	2	1	2	1	2	B	1	0.013
	So-T7-S	Net employment opportunities [T]	0-2	1	0	2	0	2	B	1	0.013
	So-T8-S	Complying health and safety practices to protect workers	1-5 scale	4	1	5	1	5	B	2	0.013
	So-R1-S	Awareness about water reuse	1-5 scale	4	1	5	1	5	B	2	0.013
	So-R2-S	Positive perception about water reuse	1-5 scale	4	1	5	1	5	B	4	0.013
	So-R3-S	Acceptance of water reuse	1-5 scale	4	1	5	1	5	B	4	0.013
	So-R4-S	Willingness to pay for water reuse	1-5 scale	4	1	5	1	5	B	4	0.013
	So-R5-S	Willingness to implement water reuse	1-5 scale	4	1	5	1	5	B	4	0.013
	So-R6-S	Net employment opportunities [R]	0-2	1	0	2	0	2	B	1	0.013
Economic - Sustainability	Ec-T1-S	Cost coverage of sanitation	%	80	0	100	0	100	B	100	0.011
	Ec-T2-S	Existence of adequate funding for treatment	Yes(2)/No(1)	2	1	2	1	2	B	2	0.011
	Ec-T3-S	Percentage of operating and maintenance costs coverage	%	80	0	100	0	100	B	100	0.011
	Ec-T4-S	Budget allocation for trainings and capacity development	Yes(2)/No(1)	2	1	2	1	2	B	2	0.011
	Ec-T5-S	Reliability of energy supply	Yes(2)/No(1)	2	1	2	1	2	B	2	0.011
	Ec-T6-S	Existence of an economic feasibility study	Yes(2)/No(1)	2	1	2	1	2	B	2	0.011
	Ec-T7-S	Existence of investment	Yes(2)/No(1)	2	1	2	1	2	B	2	0.011
	Ec-T9-S	Generation of new funds to cover additional capital costs (e.g., by energy production)	Yes(2)/No(1)	2	1	2	1	2	B	1	0.011
	Ec-T10-S	Long-term contracts and management plans	1-5 scale	4	1	5	1	5	B	4	0.011
	Ec-T11-S	Reliability of the used technology (security of supply/operation)	1-5 scale	4	1	5	1	5	B	4	0.011
	Ec-R1-S	Existence of business model	Yes(2)/No(1)	2	1	2	1	2	B	2	0.011
	Ec-R2-S	Projectable permanence of (re)user in the activity	Yes(2)/No(1)	2	1	2	1	2	B	2	0.011
	Ec-R3-S	Blockage of desirable developments	Yes(2)/No(1)	1	1	2	2	1	C	1	0.011
	Ec-R4-S	Coverage of water reuse costs	0-100%	80	0	100	0	100	B	100	0.011
	Ec-R5-S	Existence of (potential) market	Yes(2)/No(1)	2	1	2	1	2	B	2	0.011
Environmental - Sustainability	En-T2-S	Land requirement for WWTP	0-1	0.2	0.12	0.3	0.12	0.3	B	0.28	0.028
	En-T5-S	Continuity of service	1-5 scale	4	1	5	1	5	B	4	0.028
	En-T6-S	Operation and maintenance aspects	1-5 scale	4	1	5	5	1	C	3	0.028
	En-T8-S	Quality compliance of treated wastewater	Yes(2)/No(1)	2	1	2	1	2	B	2	0.028
	En-R1-S	Water quantity reused	%	80	0	100	0	100	B	100	0.028
	En-R2-S	Compliance with agricultural irrigation use quality	Yes(2)/No(1)	2	1	2	1	2	B	2	0.028

Weight Sum 0.5

Table C-3 TOPSIS calculations for the Sustainability sub-index

Decision Matrix

	So-U2-S	So-T3-S	So-T4-S	So-T5-S	So-T6-S	So-T7-S	So-T8-S	So-R1-S	So-R2-S	So-R3-S	So-R4-S	So-R5-S	So-R6-S	Ec-T1-S	Ec-T2-S	Ec-T3-S	Ec-T4-S	Ec-T5-S	Ec-T6-S	Ec-T7-S	Ec-T9-S	Ec-T10-S	Ec-T11-S	Ec-R1-S	Ec-R2-S	Ec-R3-S	Ec-R4-S	Ec-R5-S	En-T2-S	En-T5-S	En-T6-S	En-T8-S	En-R1-S	En-R2-S
Case Study	2	3	3	4	1	1	2	2	4	4	4	4	1	100	2	100	2	2	2	2	1	4	4	2	2	1	100	2	0.275634	4	3	2	100	2
Min Desirable	2	4	4	4	2	1	4	4	4	4	4	4	1	80	2	80	2	2	2	2	2	4	4	2	2	1	80	2	0.2	4	4	2	80	2
Ideal Best	2	5	5	5	2	2	5	5	5	5	5	5	2	100	2	100	2	2	2	2	2	5	5	2	2	1	100	2	0.3	5	1	2	100	2
Ideal Worst	1	1	1	1	1	0	1	1	1	1	1	1	0	0	1	0	1	1	1	1	1	1	1	1	1	2	0	1	0.12	1	5	1	0	1

Upper Limit	2	5	5	5	2	2	5	5	5	5	5	5	2	100	2	100	2	2	2	2	2	5	5	2	2	2	100	2	0.3	5	5	2	100	2
Lower Limit	1	1	1	1	1	0	1	1	1	1	1	1	0	0	1	0	1	1	1	1	1	1	1	1	1	1	0	1	0.12	1	1	1	0	1
Cost/Benefit	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	C	B	B	B	B	C	B	B	B

Normalized Decision Matrix, using Min-Max normalization method

	So-U2-S	So-T3-S	So-T4-S	So-T5-S	So-T6-S	So-T7-S	So-T8-S	So-R1-S	So-R2-S	So-R3-S	So-R4-S	So-R5-S	So-R6-S	Ec-T1-S	Ec-T2-S	Ec-T3-S	Ec-T4-S	Ec-T5-S	Ec-T6-S	Ec-T7-S	Ec-T9-S	Ec-T10-S	Ec-T11-S	Ec-R1-S	Ec-R2-S	Ec-R3-S	Ec-R4-S	Ec-R5-S	En-T2-S	En-T5-S	En-T6-S	En-T8-S	En-R1-S	En-R2-S
Case Study	1	0.5	0.5	0.75	0	0.5	0.25	0.25	0.75	0.75	0.75	0.75	0.5	1	1	1	1	1	1	1	0	0.75	0.75	1	1	1	1	1	0.864633	0.75	0.5	1	1	1
Min Desirable	1	0.75	0.75	0.75	1	0.5	0.75	0.75	0.75	0.75	0.75	0.75	0.5	0.8	1	0.8	1	1	1	1	1	0.75	0.75	1	1	1	0.8	1	0.444444	0.75	0.25	1	0.8	1
Ideal Best	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Ideal Worst	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Weights	0.0128	0.0128	0.0128	0.0128	0.0128	0.0128	0.0128	0.0128	0.0128	0.0128	0.0128	0.0128	0.0128	0.0111	0.0111	0.0111	0.0111	0.0111	0.0111	0.0111	0.0111	0.0111	0.0111	0.0111	0.0111	0.0111	0.0111	0.0111	0.0278	0.0278	0.0278	0.0278	0.0278	0.0278

Weighted Normalized Decision Matrix

	So-U2-S	So-T3-S	So-T4-S	So-T5-S	So-T6-S	So-T7-S	So-T8-S	So-R1-S	So-R2-S	So-R3-S	So-R4-S	So-R5-S	So-R6-S	Ec-T1-S	Ec-T2-S	Ec-T3-S	Ec-T4-S	Ec-T5-S	Ec-T6-S	Ec-T7-S	Ec-T9-S	Ec-T10-S	Ec-T11-S	Ec-R1-S	Ec-R2-S	Ec-R3-S	Ec-R4-S	Ec-R5-S	En-T2-S	En-T5-S	En-T6-S	En-T8-S	En-R1-S	En-R2-S
Case Study	0.0128	0.0064	0.0064	0.0096	0.0000	0.0064	0.0032	0.0032	0.0096	0.0096	0.0096	0.0096	0.0064	0.0111	0.0111	0.0111	0.0111	0.0111	0.0111	0.0111	0.0000	0.0083	0.0083	0.0111	0.0111	0.0111	0.0111	0.0111	0.0240	0.0208	0.0139	0.0278	0.0278	0.0278
Min Desirable	0.0128	0.0096	0.0096	0.0096	0.0128	0.0064	0.0096	0.0096	0.0096	0.0096	0.0096	0.0096	0.0064	0.0089	0.0111	0.0089	0.0111	0.0111	0.0111	0.0111	0.0111	0.0083	0.0083	0.0111	0.0111	0.0111	0.0089	0.0111	0.0123	0.0208	0.0069	0.0278	0.0222	0.0278
Ideal Best	0.0128	0.0128	0.0128	0.0128	0.0128	0.0128	0.0128	0.0128	0.0128	0.0128	0.0128	0.0128	0.0128	0.0111	0.0111	0.0111	0.0111	0.0111	0.0111	0.0111	0.0111	0.0111	0.0111	0.0111	0.0111	0.0111	0.0111	0.0111	0.0278	0.0278	0.0278	0.0278	0.0278	0.0278
Ideal Worst	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Positive-ideal solution for sustainability (A*_S) and Negative-ideal solution for sustainability (A-_S)

A*_S	0.0128	0.0128	0.0128	0.0128	0.0128	0.0128	0.0128	0.0128	0.0128	0.0128	0.0128	0.0128	0.0128	0.0111	0.0111	0.0111	0.0111	0.0111	0.0111	0.0111	0.0111	0.0111	0.0111	0.0111	0.0111	0.0111	0.0111	0.0111	0.0278	0.0278	0.0278	0.0278	0.0278	0.0278
A-_S	0.0000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Distance from A*_S (Si*_S), Distance from A-_S (Si-_S), Relative Closeness to A*_S (Pi*_S), and Final Ranking for Sustainability

	Si*_S	Si-_S	Si*_S + Si-_S	Pi*_S	Rank
Case Study	0.0310	0.0771	0.1081	0.7135	1
Min Desirable	0.0309	0.0743	0.1053	0.7062	N/A
Ideal Best	0	0.0928	0.0928	1	N/A
Ideal Worst	0.0928	0	0.0928	0	N/A

Table C-4 Risk indicators

Dimension	ID	Indicator	Unit/Scale	Minimum Desirable Value	Lower Limit	Upper Limit	Ideal Worst	Ideal Best	Cost/ Benefit	Case Study Data Value	Weight
Social - Risk	So-U4-R	Retaining agricultural function in water-scarce conditions	Yes (2)/No (1)	2	1	2	1	2	B	2	0.042
	So-U5-R	Retaining agricultural structure in water-scarce conditions	Yes (2)/No (1)	2	1	2	1	2	B	2	0.042
	So-U7-R	Percentage of population below poverty line	%	11.7	0	100	100	0	C	21.16	0.042
	So-U8-R	Human Development Index	0-1	0.8	0	1	0	1	B	0.74	0.042
Economic - Risk	Ec-U2-R	Unemployment rate	%	5.389	0	100	100	0	C	7.1	0.042
	Ec-U4-R	Water supplier financial solvency	%	80	0	100	0	100	B	100	0.042
	Ec-U5-R	Water supplier's ability to generate new funds to cover additional capital costs	Yes (2)/No (1)	2	1	2	1	2	B	2	0.042
	Ec-T8-R	Existence of governement support	Yes (2)/No (1)	2	1	2	1	2	B	2	0.042
Environmental - Risk	En-S4-R	Ratio of water resources in storage	%	80	0	100	0	100	B	70.34	0.056
	En-S5-R	Existence of an emitted water scarcity decree for the area in the assessed period	Yes (2)/No (1)	1	2	1	2	1	B	2	0.056
	En-S6-R	Level of water scarcity	1-4 scale	1	1	4	4	1	C	1	0.056
										Weight Sum	0.5

Table C-5 TOPSIS calculations for the Risk sub-index

Decision Matrix

	So-U4-R	So-U5-R	So-U7-R	So-U8-R	Ec-U2-R	Ec-U4-R	Ec-U5-R	Ec-T8-R	En-S4-R	En-S5-R	En-S6-R
Case Study	2	2	21.16	0.74	7.1	100	2	2	70.33742	2	1
Min Desirable	2	2	11.7	0.8	5.389	80	2	2	80	1	1
Ideal Best	2	2	0	1	0	100	2	2	100	1	1
Ideal Worst	1	1	100	0	100	0	1	1	0	2	4

Upper Limit	2	2	100	1	100	100	2	2	100	1	4
Lower Limit	1	1	0	0	0	0	1	1	0	2	1
Cost/Benefit	B	B	C	B	C	B	B	B	B	B	C

Normalized Decision Matrix, using Min-Max normalization method

	So-U4-R	So-U5-R	So-U7-R	So-U8-R	Ec-U2-R	Ec-U4-R	Ec-U5-R	Ec-T8-R	En-S4-R	En-S5-R	En-S6-R
Case Study	1	1	0.7884	0.74	0.929	1	1	1	0.703374	0	1
Min Desirable	1	1	0.883	0.8	0.94611	0.8	1	1	0.8	1	1
Ideal Best	1	1	1	1	1	1	1	1	1	1	1
Ideal Worst	0	0	0	0	0	0	0	0	0	0	0

Weights	0.04167	0.04167	0.041666667	0.04167	0.04167	0.04167	0.04167	0.04167	0.055556	0.055556	0.055556

Weighted Normalized Decision Matrix

	So-U4-R	So-U5-R	So-U7-R	So-U8-R	Ec-U2-R	Ec-U4-R	Ec-U5-R	Ec-T8-R	En-S4-R	En-S5-R	En-S6-R
Case Study	0.0417	0.0417	0.03285	0.03083	0.0387	0.0417	0.0417	0.0417	0.0391	0.0000	0.0556
Min Desirable	0.0417	0.0417	0.0368	0.0333	0.0394	0.0333	0.0417	0.0417	0.0444	0.0556	0.0556
Ideal Best	0.0417	0.0417	0.0417	0.0417	0.0417	0.0417	0.0417	0.0417	0.0556	0.0556	0.0556
Ideal Worst	0	0	0	0	0	0	0	0	0	0	0

Positive-ideal solution for risk (A*_R) and Negative-ideal solution for risk (A-_R)

A*_R	0.0417	0.0417	0.0417	0.0417	0.0417	0.0417	0.0417	0.0417	0.0556	0.0556	0.0556
A-_R	0	0	0	0	0	0	0	0	0	0	0

Distance from A*_R (Si*_R), Distance from A-_R (Si-_R), Relative Closeness to A*_R (Pi*_R), and Final Ranking for Risk

	Si*_R	Si-_R	Si*_R + Si-_R	Pi*_R	Rank
Case Study	0.0597	0.1297	0.1894	0.6849	1
Min Desirable	0.0171	0.1422	0.1593	0.8929	N/A
Ideal Best	0	0.1521	0.1521	1	N/A
Ideal Worst	0.1521	0	0.1521	0	N/A

Table C-6 TOPSIS calculation for the aggregation of the final RSA index

Decision Matrix

	Pi*_S	Pi*_R
Case Study	0.7135	0.6849
Min Desirable	0.7062	0.8929
Ideal Best	1.0000	1.0000
Ideal Worst	0.0000	0.0000

Upper Limit	1.0000	1.0000
Lower Limit	0.0000	0.0000
Cost/Benefit	B	B

Normalized Decision Matrix, using Min-Max normalization method

	Pi*_S	Pi*_R
Case Study	0.71353	0.68486
Min Desirable	0.70622	0.89287
Ideal Best	1	1
Ideal Worst	0	0

Weights	0.5	0.5

Weighted Normalized Decision Matrix

	Pi*_S	Pi*_R
Case Study	0.3568	0.3424
Min Desirable	0.3531	0.4464
Ideal Best	0.5000	0.5000
Ideal Worst	0	0

Positive-ideal solution (A*) and Negative-ideal solution (A-)

A*	0.5000	0.5000
A-	0	0

Distance from A* (Si*), Distance from A- (Si-), Relative Closeness to A* (Pi*), and Final Ranking

	Si*	Si-	Si* + Si-	Pi*	Rank
Case Study	0.2129	0.4945	0.7075	0.6990	1
Min Desirable	0.1564	0.5692	0.7256	0.7845	N/A
Ideal Best	0	0.7071	0.7071	1	N/A
Ideal Worst	0.7071	0	0.7071	0	N/A

Annex D - Translation into the Information System (from endpoints to attributes)

Supplementary material (SM-B) of the scientific publication in Chapter 4.

Table D-7: List of endpoints, descriptors, indicators, and attributes. Dim.: Dimension; So: Social; Ec: Economic; En: Environmental; R: Risk; S: Sustainability.

Process category	Box in CHANS	Endpoint	Dim.	Descriptor	Indicator	Attribute	Source	Type of indicator *R: Risk; S: Sustainability*
Source	**Weather and climate**							
		Input of water resources	En	Precipitation	Standardised Precipitation Index (SPI 1-5 months)	Monthly precipitation value over 30 years Precipitation in analysed month(s)	From [1]	R
	Catchment							
		Water in river basin	So	Catchment water resources management plan	Existence of a water resources management plan at a catchment level	Number of water resources management plans	Defined by authors	R
			En	Surface water flow	Standardised Surface flow Index (SSFI 3 consecutive months)	Surface water flow values over 30 years Surface water flow values of past 3 consecutive months	From [1]	R
	Water availability							
		Available surface water	Ec	Costs of water withdrawal	Coverage of water withdrawal costs	Costs of water withdrawal Budget allocated for water withdrawal	Defined by authors	R
			En	Quantity of surface water resources withdrawn	Increase in water withdrawal	Average agricultural sector water withdrawals Agricultural sector water withdrawals in analysed year	Adapter from [2]	R
				Quantity of surface water resources available for human use	Percentage water resources in storage (compared to historical average)	Average quantity of water resources in analysed period over the past 30 years Quantity of water resources in assessed period	Adapted from [1,2]	R
				Situation of water scarcity	Existence of an emitted water scarcity decree for the area in the assessed period	Number of water scarcity decrees emitted by the Water Authority in the assessed period	Defined by authors	R
					Level of water scarcity	Quantity of water resources available for human use (in analysed year) Quantity of water resources demanded for agricultural irrigation (in analysed year)	Adapted from [3]	R
	Ecosystem							

Process category	Box in CHANS	Endpoint	Dim.	Descriptor	Indicator	Attribute	Source	Type of indicator *R: Risk; S: Sustainability*
		Ecosystem water requirement	En	Quantity of water required to maintain the ecosystem	Increase in ecosystem water demand	Average quantity of water resources demanded to maintain the ecosystem Quantity of water resources demanded to maintain the ecosystem (in analysed year)	Adapted from [4]	R
				Environmental degradation	Decrease of biodiversity in the source area	Average number of species (flora and fauna) in area Number of species (flora and fauna) in area (in analysed year)	Adapted from [5]	R
Use	**Water use**							
		Used water resources	So	Water supply	Percentage of access to water supply	Total farmers requiring access to water supply Farmers with access to water supply	Adapted from[6,7]	R
					24-hour water supply availability	Hours per day in with secured water supply	From [8]	S
				Employment provided by the farmer	Dependence on agriculture for jobs	Total jobs offered in area Employment related to agriculture	Adapted from [9,10]	R
				Retaining agricultural function and structure in water-scarce conditions	Retaining agricultural function in water-scarce conditions	Agricultural production in a non-water-scarce year Agricultural production in a water-scarce year	Adapted from [11]	R
					Retaining agricultural structure in water-scarce conditions	Employment related to agriculture in non-water-scarce year Employment related to agriculture in water-scarce year Productive land in a non-water-scarce year Productive land in a water-scarce year	Adapted from [11]	R
					Controllability of impacts of water scarcity	Total population in study area Population reporting a positive perception about ability to control impacts of water scarcity	Adapted from [11]	R
				Social vulnerability	Percentage of population below poverty line	Population below poverty line [inhab.] Total population of area [inhab.]	Adapted from [10,12]	R
					Human Development Index	Health: Life expectancy (years) Education: expected years of schooling Education: mean years of schooling	From [7]	R

Process category	Box in CHANS	Endpoint	Dim.	Descriptor	Indicator	Attribute	Source	Type of indicator *R: Risk; S: Sustainability*
						Standard of living: GNI per capita (2017 PPP$)		
			Ec	Economic loss due to water scarcity	Economic loss due to water scarcity	Agricultural costs in a water-scarce year Agricultural income in a water-scarce year	Defined by authors	R
				Economic vulnerability	Unemployment rate	Average unemployment rate in area Unemployment in analysed year	Adapted from [13]	R
					Decrease in agricultural income	Average annual income Annual income (in analysed year)	Adapted from [14]	R
					Water supplier financial solvency	Cost of water supply Financial resources for water supply	Adapted from [5]	R
					Water supplier's ability to generate new funds to cover additional capital costs	Number of a economic risk mitigation plans	Adapted from [5]	R
		General aspects (transversal to domestic, ind. & agri. uses)	So	Awareness of water scarcity	Awareness of water scarcity	Population reporting to know about water scarcity Total population in study area	Defined by authors	R
			So	Perception of water scarcity	Perception of water scarcity	Positive attitude towards wate scarcity	Defined by authors	R
			En	Water use efficiency	Irrigation efficiency	Water losses during irrigation Total water used for irrigation	Adapted from [15]	R
Treatment	**Water sanitation**							
		Discharged wastewater	So	Sanitation coverage	Percentage of population connected to water sanitation	Total population in study area Total population connected to sanitation	Adapted from [7]	S
			Ec	Cost coverage of sanitation	Cost coverage of sanitation	Total cost of sanitation Budget allocated for sanitation	Defined by authors	S
			En	Quantity of wastewater transported to WWTP	Wastewater leakage	Quantity of wastewater transported to WWTP Quantity of wastewater lost/leaked	Adapted from [5]	S
	Wastewater treatment							
		Wastewater in WWTP	So	Wastewater treatment coverage	Percentage of population connected to wastewater treatment	Total population in study area	Adapted from [5,7]	S

Process category	Box in CHANS	Endpoint	Dim.	Descriptor	Indicator	Attribute	Source	Type of indicator *R: Risk; S: Sustainability*
						Population connected to wastewater treatment		
					Willingness to pay for sanitation and treatment	Total population in study area Population willing to pay for wastewater treatment	Adapted from [8]	S
				Awareness of the role of WWTP	Awareness about WWTP (community)	Total population in study area Population reporting knowing about the WWTP	Defined by authors	S
				Perception and acceptance of WWTP	Positive perception about WWT (community)	Total population in study area Population reporting positive perception about the WWTP	Defined by authors	S
					Complaints among neighbours of WWTS	Total neighbours of WWTP Neighbours complaining about WWTP	Adapted from [16]	S
			En	Land area requirement	Land requirement for WWTP	Land requirement of WWTP Total inhabitants connected to WWTP Total area available for WWTP	Adapted from [5]	S
		Wastewater treatment operation and maintenance	So	Employment	Net employment opportunities [T]	Number of employment opportunities created in analysed year (by the WWTP) Number of employment opportunities eliminated in analysed year (by the WWTP)	Adapted from [17,18]	S
			So	Workers' health and security measures	Complying health and safety practices to protect workers	Total inspections in a year Total inspections approved in a year	Adapted from [18]	S
			Ec	Cost coverage of wastewater treatment	Existence of adequate funding for treatment	Income from treatment fees (per capita)	Defined by authors	S
					Percentage of operating and maintenance costs coverage	Specific cost of WWT (e.g., USD/m3) Budget allocated for operation and maintenance costs	Adapted from [5]	S
					Budget allocation for trainings and capacity development	Annual costs of training and capacity development Budget allocated for trainings and capacity development		S
					Reliability of energy supply	Stable energy supply Existence of back-up energy source	Adapted from [19]	S
				Economic feasibility	Existence of a economic feasibility study	Number of a economic feasibility study	Defined by authors	S

Process category	Box in CHANS	Endpoint	Dim.	Descriptor	Indicator	Attribute	Source	Type of indicator *R: Risk; S: Sustainability*
				Financial security	Existence of investment	Number of investment sources	Defined by authors	S
					Existence of government support	Number of government support sources	From [20]	R
					Generation of new funds to cover additional capital costs (e.g. by energy production)	Number of business plans providing new income sources	Adapted from [5]	S
					Long-term contracts and management plans	Number of total workers Number of total long-term contracts	Adapted from [21]	S
					Reliability of the used technology (security of supply/operation)	Share of failures in a year	Adapted from [21]	S
			En	Energy consumption	Specific energy use	Energy consumption per m3 of TWW	Adapted from [5]	S
				Water losses	Water losses	Total wastewater to be treated Water leaked in WWT process	Adapted from [5]	S
				Compliance with standards	Continuity of service	Hours per day in without stop	Adapted from [5]	S
					Operation and maintenance aspects	Level of operational and maintenance requirements		S
				Technical feasibility	Existence of a technical feasibility study	Number of technical feasibility reports	Defined by authors	S
	Treated wastewater (TWW)							
		Treated wastewater	En	Treated wastewater quality	Quality compliance of treated wastewater	Total number of TWW quality audits in a year Number of approved TWW quality audits in a year	Adapted from [5]	S
	Sludge							
		Sludge production	En	Sludge stabilisation	Sludge stabilisation and safe disposal	Existence of a stabilisation process Existence of a disposal procedure	Adapted from [5]	S
Reuse	**Human water reuse**							
		Treated wastewater for agricultural use	En	Quantity of TWW reused in agriculture	Water quantity reused	Quantity of TWW Quantity of TWW reused	Adapted from [5]	S
		General aspects of water reuse (transversal to domestic, ind. & agri. uses)	So	Awareness of water reuse	Awareness about water reuse	Total population in study area Population reporting knowing about reuse	Defined by authors	S
				Perception and acceptance of water reuse	Positive perception about water reuse	Total population in study area	Defined by authors	S

Process category	Box in CHANS	Endpoint	Dim.	Descriptor	Indicator	Attribute	Source	Type of indicator *R: Risk; S: Sustainability*
						Population with positive perception of water reuse		
					Acceptance of water reuse	Total population in study area Population reporting accepting water reuse	Adapted from [22]	S
					Willingness to pay for water reuse	Total population in study area Population reporting being willing to pay for water reuse	Adapted from [8]	S
					Willingness to implement water reuse	Total population in study area Population reporting being willing to implement water reuse	Defined by authors	S
				Employment	Net employment opportunities [R]	Number of new employment opportunities created	Adapted from [17,18]	S
			Ec	Economic feasibility	Existence of business model	Existence of business model	Defined by authors	S
					Projectable permanence of (re)user in the activity	Projectable permanence of (re)user in the activity	Adapted from [23]	S
					Blockage of desirable developments	Number of other projects blocked	Adapted from [21]	S
					Coverage of water reuse costs	Costs for treated wastewater distribution Budget allocated for water reuse	Adapted from [16]	S
					Existence of (potential) market	Existence of (potential) market	Adapted from [23]	S
			En	Technical feasibility of water reuse	Compliance with agricultural irrigation use quality	Number of quality tests carried out in a year Number of quality test approved in a year	Adapted from [5]	S

References Annex C

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Annex E - Interlinkages Identification Matrix

Supplementary material (SM-C) of the scientific publication in Chapter 4.

Figure E-1: Overview of the complete interlinkage identification matrix.

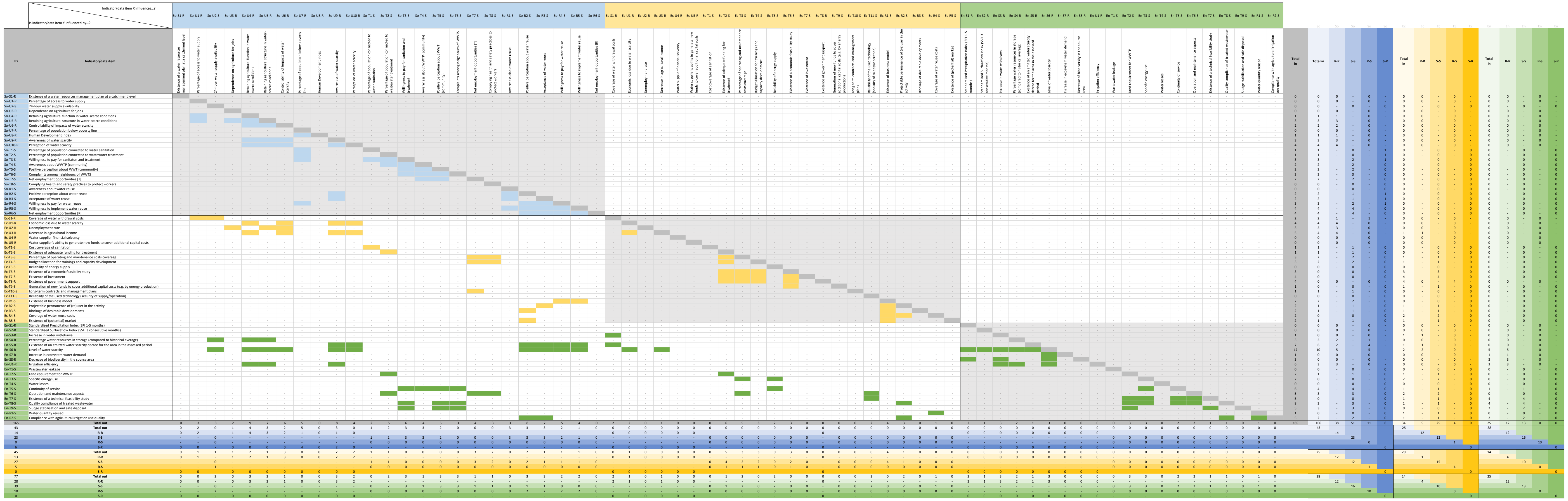
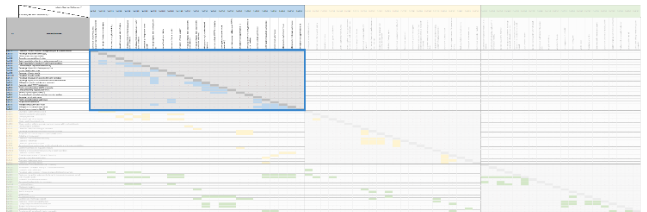
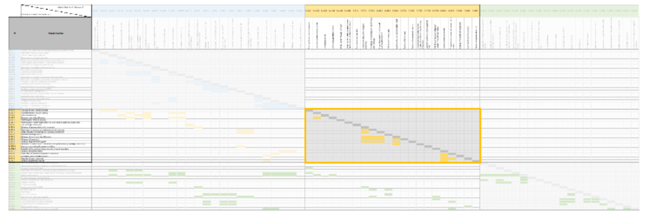


Figure E-2: Social Intra-dimensional interlinkages



		So-S1-R	So-U1-R	So-U2-S	So-U3-R	So-U4-R	So-U5-R	So-U6-R	So-U7-R	So-U8-R	So-U9-R	So-U10-R	So-T1-S	So-T2-S	So-T3-S	So-T4-S	So-T5-S	So-T6-S	So-T7-S	So-T8-S	So-R1-S	So-R2-S	So-R3-S	So-R4-S	So-R5-S	So-R6-S					
ID	Indicator/data item	Existence of a water resources management plan at a catchment level	Percentage of access to water supply	24-hour water supply availability	Dependence on agriculture for jobs	Retaining agricultural function in water-scarce conditions	Retaining agricultural structure in water-scarce conditions	Controllability of impacts of water scarcity	Percentage of population below poverty line	Human Development Index	Awareness of water scarcity	Perception of water scarcity	Percentage of population connected to water sanitation	Percentage of population connected to wastewater treatment	Willingness to pay for sanitaton and treatment	Awareness about WWTP (community)	Positive perception about WWT (community)	Complaints among neighbours of WWTS	Net employment opportunities [T]	Complying health and safety practices to protect workers	Awareness about water reuse	Positive perception about water reuse	Acceptance of water reuse	Willingness to pay for water reuse	Willingness to implement water reuse	Net employment opportunities [R]	Total in	R-R	S-S	R-S	S-R
So-S1-R	Existence of a water resources management plan at a catchment level		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	0	-	0	-
So-U1-R	Percentage of access to water supply	-		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	0	-	0	-
So-U2-S	24-hour water supply availability	-	-		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	-	0	-	0
So-U3-R	Dependence on agriculture for jobs	-	-	-		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	0	-	0	-
So-U4-R	Retaining agricultural function in water-scarce conditions	-		-	-		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	1	-	0	-
So-U5-R	Retaining agricultural structure in water-scarce conditions	-		-				-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	3	3	-	0	-
So-U6-R	Controllability of impacts of water scarcity	-	-	-	-				-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2	2	-	0	-
So-U7-R	Percentage of population below poverty line	-	-	-	-	-	-	-		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	0	-	0	-
So-U8-R	Human Development Index	-	-	-	-	-	-	-			-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	1	-	0	-
So-U9-R	Awareness of water scarcity	-	-	-	-				-	-		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	3	3	-	0	-
So-U10-R	Perception of water scarcity	-	-	-	-				-	-			-	-	-	-	-	-	-	-	-	-	-	-	-	-	4	4	-	0	-
So-T1-S	Percentage of population connected to water sanitation	-	-	-	-	-	-	-		-	-	-		-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	0	-	1
So-T2-S	Percentage of population connected to wastewater treatment	-	-	-	-	-	-	-		-	-	-	-		-	-	-	-	-	-	-	-	-	-	-	-	1	-	0	-	1
So-T3-S	Willingness to pay for sanitaton and treatment	-	-	-	-	-	-	-		-	-	-				-	-	-	-	-	-	-	-	-	-	-	3	-	2	-	1
So-T4-S	Awareness about WWTP (community)	-	-	-	-	-	-	-	-	-	-	-	-				-	-	-	-	-	-	-	-	-	-	2	-	2	-	0
So-T5-S	Positive perception about WWT (community)	-	-	-	-	-	-	-	-	-	-	-	-	-				-	-	-	-	-	-	-	-	-	2	-	2	-	0
So-T6-S	Complaints among neighbours of WWTS	-	-	-	-	-	-	-	-	-	-	-	-	-					-	-	-	-	-	-	-	-	3	-	3	-	0
So-T7-S	Net employment opportunities [T]	-	-	-	-	-	-	-	-	-	-	-	-	-	-			-		-	-	-	-	-	-	-	2	-	2	-	0
So-T8-S	Complying health and safety practices to protect workers	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		-	-	-	-	-	-	0	-	0	-	0
So-R1-S	Awareness about water reuse	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		-	-	-	-	-	0	-	0	-	0
So-R2-S	Positive perception about water reuse	-	-	-	-	-	-	-	-	-		-	-	-	-	-	-	-	-	-			-	-	-	-	2	-	1	-	1
So-R3-S	Acceptance of water reuse	-	-	-	-	-	-	-	-	-		-	-	-	-	-	-	-	-	-		-		-	-	-	2	-	1	-	1
So-R4-S	Willingness to pay for water reuse	-	-	-	-	-	-	-		-	-	-	-	-	-	-	-	-	-	-	-				-	-	3	-	2	-	1
So-R5-S	Willingness to implement water reuse	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-						-	4	-	4	-	0
So-R6-S	Net employment opportunities [R]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-						4	-	4	-	0
43	**Total out**	0	2	0	1	4	3	2	5	0	3	0	1	2	3	3	2	0	0	0	3	3	3	2	1	0	43	14	23	0	6
14	**R-R**	0	2	-	1	4	3	2	1	0	1	0	-	-	-	-	-	-	-	-	-	-	-	-	-	-		OK			
23	**S-S**	-	-	0	-	-	-	-	-	-	-	-	1	2	3	3	2	0	0	0	3	3	3	2	1	0			OK		
0	**R-S**	-	-	0	-	-	-	-	-	-	-	-	0	0	0	0	0	0	0	0	0	0	0	0	0	0				OK	
6	**S-R**	0	0	-	0	0	0	0	4	0	2	0	-	-	-	-	-	-	-	-	-	-	-	-	-	-					OK

Figure E-3: Economic Intra-dimensional interlinkages

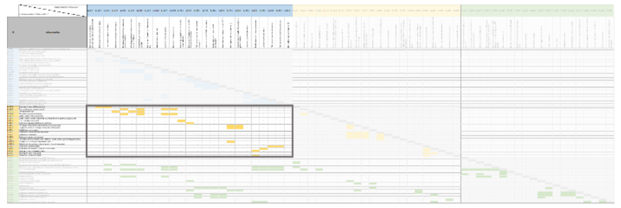


ID	Indicator/data item	Ec-S1-R	Ec-U1-R	Ec-U2-R	Ec-U3-R	Ec-U4-R	Ec-U5-R	Ec-T1-S	Ec-T2-S	Ec-T3-S	Ec-T4-S	Ec-T5-S	Ec-T6-S	Ec-T7-S	Ec-T8-R	Ec-T9-S	Ec-T10-S	Ec-T11-S	Ec-R1-S	Ec-R2-S	Ec-R3-S	Ec-R4-S	Ec-R5-S	Total in	R-R	S-S	R-S	S-R
		Coverage of water withdrawal costs	Economic loss due to water scarcity	Unemployment rate	Decrease in agricultural income	Water supplier financial solvency	Water supplier's ability to generate new funds to cover additional capital costs	Cost coverage of sanitation	Existence of adequate funding for treatment	Percentage of operating and maintenance costs coverage	Budget allocation for trainings and capacity development	Reliability of energy supply	Existence of a economic feasibility study	Existence of investment	Existence of government support	Generation of new funds to cover additional capital costs (e.g. by energy production)	Long-term contracts and management plans	Reliability of the used technology (security of supply/operation)	Existence of business model	Projectable permanence of (re)user in the activity	Blockage of desirable developments	Coverage of water reuse costs	Existence of (potential) market					
Ec-S1-R	Coverage of water withdrawal costs		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	0	-	0	-
Ec-U1-R	Economic loss due to water scarcity	-		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	0	-	0	-
Ec-U2-R	Unemployment rate	-	-		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	0	-	0	-
Ec-U3-R	Decrease in agricultural income	-		-		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	1	-	0	-
Ec-U4-R	Water supplier financial solvency	-	-	-	-		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	0	-	0	-
Ec-U5-R	Water supplier's ability to generate new funds to cover additional capital costs	-	-	-	-	-		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	0	-	0	-
Ec-T1-S	Cost coverage of sanitation	-	-	-	-	-	-		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	-	0	-	0
Ec-T2-S	Existence of adequate funding for treatment	-	-	-	-	-	-	-		-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	-	0	-	0
Ec-T3-S	Percentage of operating and maintenance costs coverage	-	-	-	-	-	-	-			-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	1	-	0
Ec-T4-S	Budget allocation for trainings and capacity development	-	-	-	-	-	-	-		-		-	-	-	-	-	-	-	-	-	-	-	-	1	-	1	-	0
Ec-T5-S	Reliability of energy supply	-	-	-	-	-	-	-	-	-	-		-	-	-	-	-	-	-	-	-	-	-	0	-	0	-	0
Ec-T6-S	Existence of a economic feasibility study	-	-	-	-	-	-	-				-		-	-	-	-	-	-	-	-	-	-	3	-	3	-	0
Ec-T7-S	Existence of investment	-	-	-	-	-	-	-				-			-	-	-	-	-	-	-	-	-	4	-	4	-	0
Ec-T8-R	Existence of government support	-	-	-	-	-	-	-				-		-		-	-	-	-	-	-	-	-	4	0	-	4	-
Ec-T9-S	Generation of new funds to cover additional capital costs (e.g. by energy production)	-	-	-	-	-	-	-	-	-	-	-		-	-		-	-	-	-	-	-	-	1	-	1	-	0
Ec-T10-S	Long-term contracts and management plans	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		-	-	-	-	-	-	0	-	0	-	0
Ec-T11-S	Reliability of the used technology (security of supply/operation)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		-	-	-	-	-	0	-	0	-	0
Ec-R1-S	Existence of business model	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		-	-	-	-	0	-	0	-	0
Ec-R2-S	Projectable permanence of (re)user in the activity	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-			-	-	-	1	-	1	-	0
Ec-R3-S	Blockage of desirable developments	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		-		-	-	1	-	1	-	0
Ec-R4-S	Coverage of water reuse costs	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-			-		-	2	-	2	-	0
Ec-R5-S	Existence of (potential) market	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		-	-	-		1	-	1	-	0
20	**Total out**	0	1	0	0	0	0	0	5	3	3	0	3	0	0	0	0	0	4	1	0	0	0	20	1	15	4	0
1	**R-R**	0	1	0	0	0	0	-	-	-	-	-	-	-	0	-	-	-	-	-	-	-	-		OK			
15	**S-S**	-	-	-	-	-	-	0	4	2	2	0	2	0	-	0	0	0	4	1	0	0	0			OK		
4	**R-S**	-	-	-	-	-	-	0	1	1	1	0	1	0	-	0	0	0	0	0	0	0	0				OK	
0	**S-R**	0	0	0	0	0	0	-	-	-	-	-	-	-	0	-	-	-	-	-	-	-	-					OK

Figure E-4: Environmental Intra-dimensional interlinkages

		En-S1-R	En-S2-R	En-S3-R	En-S4-R	En-S5-R	En-S6-R	En-S7-R	En-S8-R	En-U1-R	En-T1-S	En-T2-S	En-T3-S	En-T4-S	En-T5-S	En-T6-S	En-T7-S	En-T8-S	En-T9-S	En-R1-S	En-R2-S					
ID	Indicator/data item	Standardised Precipitation Index (SPI 1-5 months)	Standardised Surfaceflow Index (SSFI 3 consecutive months)	Increase in water withdrawal	Percentage water resources in storage (compared to historical average)	Existence of an emitted water scarcity decree for the area in the assessed period	Level of water scarcity	Increase in ecosystem water demand	Decrease of biodiversity in the source area	Irrigation efficiency	Wastewater leakage	Land requirement for WWTP	Specific energy use	Water losses	Continuity of service	Operation and maintenance aspects	Existence of a technical feasibility study	Quality compliance of treated wastewater	Sludge stabilisation and safe disposal	Water quantity reused	Compliance with agricultural irrigation use quality	Total in	R-R	S-S	R-S	S-R
En-S1-R	Standardised Precipitation Index (SPI 1-5 months)		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	0	-	0	-
En-S2-R	Standardised Surfaceflow Index (SSFI 3 consecutive months)	-		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	0	-	0	-
En-S3-R	Increase in water withdrawal	-	-		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	0	-	0	-
En-S4-R	Percentage water resources in storage (compared to historical average)	-	-	-		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	0	-	0	-
En-S5-R	Existence of an emitted water scarcity decree for the area in the assessed period	-	-	-	-		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	0	-	0	-
En-S6-R	Level of water scarcity							-	-	-	-	-	-	-	-	-	-	-	-	-	-	5	5	-	0	-
En-S7-R	Increase in ecosystem water demand	-	-	-	-	-			-	-	-	-	-	-	-	-	-	-	-	-	-	1	1	-	0	-
En-S8-R	Decrease of biodiversity in the source area		-		-	-		-		-	-	-	-	-	-	-	-	-	-	-	-	3	3	-	0	-
En-U1-R	Irrigation efficiency	-	-			-		-	-		-	-	-	-	-	-	-	-	-	-	-	3	3	-	0	-
En-T1-S	Wastewater leakage	-	-	-	-	-	-	-	-	-		-	-	-	-	-	-	-	-	-	-	0	-	0	-	0
En-T2-S	Land requirement for WWTP	-	-	-	-	-	-	-	-	-	-		-	-	-	-	-	-	-	-	-	0	-	0	-	0
En-T3-S	Specific energy use	-	-	-	-	-	-	-	-	-	-	-		-	-	-	-	-	-	-	-	0	-	0	-	0
En-T4-S	Water losses	-	-	-	-	-	-	-	-	-	-	-	-		-	-	-	-	-	-	-	0	-	0	-	0
En-T5-S	Continuity of service	-	-	-	-	-	-	-	-	-	-	-		-		-	-	-	-	-	-	1	-	1	-	0
En-T6-S	Operation and maintenance aspects	-	-	-	-	-	-	-	-	-	-	-	-	-	-		-	-	-	-	-	0	-	0	-	0
En-T7-S	Existence of a technical feasibility study	-	-	-	-	-	-	-	-	-	-			-				-	-	-	-	4	-	4	-	0
En-T8-S	Quality compliance of treated wastewater	-	-	-	-	-	-	-	-	-	-			-			-		-	-	-	4	-	4	-	0
En-T9-S	Sludge stabilisation and safe disposal	-	-	-	-	-	-	-	-	-	-		-	-	-	-		-		-	-	2	-	2	-	0
En-R1-S	Water quantity reused	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		-	0	-	0	-	0
En-R2-S	Compliance with agricultural irrigation use quality	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		-			2	-	2	-	0
25	**Total out**	2	1	3	2	1	3	0	0	0	0	3	3	0	2	2	1	1	0	1	0	25	12	13	0	0
12	**R-R**	2	1	3	2	1	3	0	0	0	-	-	-	-	-	-	-	-	-	-	-		OK			
13	**S-S**	-	-	-	-	-	-	-	-	-	0	3	3	0	2	2	1	1	0	1	0			OK		
0	**R-S**	-	-	-	-	-	-	-	-	-	0	0	0	0	0	0	0	0	0	0	0				OK	
0	**S-R**	0	0	0	0	0	0	0	0	0	-	-	-	-	-	-	-	-	-	-	-					OK

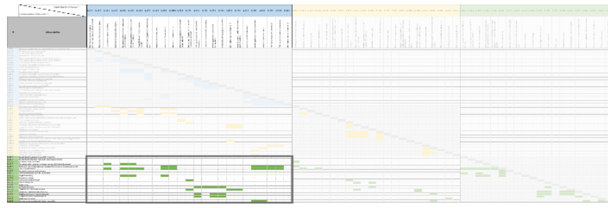
Figure E-5: Social-Economic Inter-dimensional interlinkages



Indicator/data item X influences...? / Is indicator/data item Y influenced by...?

ID	Indicator/data item	So-S1-R Existence of a water resources management plan at a catchment level	So-U1-R Percentage of access to water supply	So-U2-S 24-hour water supply availability	So-U3-R Dependence on agriculture for jobs	So-U4-R Retaining agricultural function in water-scarce conditions	So-U5-R Retaining agricultural structure in water-scarce conditions	So-U6-R Controllability of impacts of water scarcity	So-U7-R Percentage of population below poverty line	So-U8-R Human Development Index	So-U9-R Awareness of water scarcity	So-U10-R Perception of water scarcity	So-T1-S Percentage of population connected to water sanitation	So-T2-S Percentage of population connected to wastewater treatment	So-T3-S Willingness to pay for sanitaton and treatment	So-T4-S Awareness about WWTP (community)	So-T5-S Positive perception about WWT (community)	So-T6-S Complaints among neighbours of WWTS	So-T7-S Net employment opportunities [T]	So-T8-S Complying health and safety practices to protect workers	So-R1-S Awareness about water reuse	So-R2-S Positive perception about water reuse	So-R3-S Acceptance of water reuse	So-R4-S Willingness to pay for water reuse	So-R5-S Willingness to implement water reuse	So-R6-S Net employment opportunities [R]
Ec-S1-R	Coverage of water withdrawal costs	-			-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ec-U1-R	Economic loss due to water scarcity	-	-	-	-		-		-	-			-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ec-U2-R	Unemployment rate	-	-	-		-			-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ec-U3-R	Decrease in agricultural income	-	-	-	-		-		-	-			-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ec-U4-R	Water supplier financial solvency	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ec-U5-R	Water supplier's ability to generate new funds to cover additional capital costs	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ec-T1-S	Cost coverage of sanitation	-	-	-	-	-	-	-	-	-	-	-		-	-	-	-	-	-	-	-	-	-	-	-	-
Ec-T2-S	Existence of adequate funding for treatment	-	-	-	-	-	-	-	-	-	-	-	-		-	-	-	-	-	-	-	-	-	-	-	-
Ec-T3-S	Percentage of operating and maintenance costs coverage	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-			-	-	-	-	-	-
Ec-T4-S	Budget allocation for trainings and capacity development	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-			-	-	-	-	-	-
Ec-T5-S	Reliability of energy supply	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ec-T6-S	Existence of a economic feasibility study	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ec-T7-S	Existence of investment	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ec-T8-R	Existence of government support	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ec-T9-S	Generation of new funds to cover additional capital costs (e.g. by energy production)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ec-T10-S	Long-term contracts and management plans	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		-	-	-	-	-	-	-
Ec-T11-S	Reliability of the used technology (security of supply/operation)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ec-R1-S	Existence of business model	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-			-
Ec-R2-S	Projectable permanence of (re)user in the activity	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		-	-	-
Ec-R3-S	Blockage of desirable developments	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		-	-	-	-
Ec-R4-S	Coverage of water reuse costs	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ec-R5-S	Existence of (potential) market	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		-	-	-	-

Figure E-6: Social-Environmental Inter-dimensional interlinkages

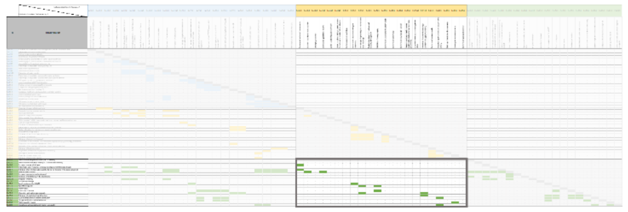


Indicator/data item X influences…?

Is indicator/data item Y influenced by…?

ID	Indicator/data item	So-S1-R Existence of a water resources management plan at a catchment level	So-U1-R Percentage of access to water supply	So-U2-S 24-hour water supply availability	So-U3-R Dependence on agriculture for jobs	So-U4-R Retaining agricultural function in water-scarce conditions	So-U5-R Retaining agricultural structure in water-scarce conditions	So-U6-R Controllability of impacts of water scarcity	So-U7-R Percentage of population below poverty line	So-U8-R Human Development Index	So-U9-R Awareness of water scarcity	So-U10-R Perception of water scarcity	So-T1-S Percentage of population connected to water sanitation	So-T2-S Percentage of population connected to wastewater treatment	So-T3-S Willingness to pay for sanitaton and treatment	So-T4-S Awareness about WWTP (community)	So-T5-S Positive perception about WWT (community)	So-T6-S Complaints among neighbours of WWTS	So-T7-S Net employment opportunities [T]	So-T8-S Complying health and safety practices to protect workers	So-R1-S Awareness about water reuse	So-R2-S Positive perception about water reuse	So-R3-S Acceptance of water reuse	So-R4-S Willingness to pay for water reuse	So-R5-S Willingness to implement water reuse	So-R6-S Net employment opportunities [R]
En-S1-R	Standardised Precipitation Index (SPI 1-5 months)	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
En-S2-R	Standardised Surfaceflow Index (SSFI 3 consecutive months)	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
En-S3-R	Increase in water withdrawal	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
En-S4-R	Percentage water resources in storage (compared to historical average)	–	–		–			–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
En-S5-R	Existence of an emitted water scarcity decree for the area in the assessed period	–	–	–	–	–	–	–	–	–			–	–	–	–	–	–	–	–	–					–
En-S6-R	Level of water scarcity	–	–		–				–	–			–	–	–	–	–	–	–	–	–					–
En-S7-R	Increase in ecosystem water demand	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
En-S8-R	Decrease of biodiversity in the source area	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
En-U1-R	Irrigation efficiency	–	–	–	–			–	–	–		–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
En-T1-S	Wastewater leakage	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
En-T2-S	Land requirement for WWTP	–	–	–	–	–	–	–	–	–	–	–	–		–	–	–	–	–	–	–	–	–	–	–	–
En-T3-S	Specific energy use	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
En-T4-S	Water losses	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
En-T5-S	Continuity of service	–	–	–	–	–	–	–	–	–	–	–	–	–					–	–	–	–	–	–	–	–
En-T6-S	Operation and maintenance aspects	–	–	–	–	–	–	–	–	–	–	–	–		–	–	–	–			–	–	–	–	–	–
En-T7-S	Existence of a technical feasibility study	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
En-T8-S	Quality compliance of treated wastewater	–	–	–	–	–	–	–	–	–	–	–	–	–		–			–	–	–	–	–	–	–	–
En-T9-S	Sludge stabilisation and safe disposal	–	–	–	–	–	–	–	–	–	–	–	–	–		–			–	–	–	–	–	–	–	–
En-R1-S	Water quantity reused	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
En-R2-S	Compliance with agricultural irrigation use quality	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–			–	–	–

Figure E-7: Economic-Environmental Inter-dimensional interlinkages



Indicator/data item X influences...?

Is indicator/data item Y influenced by...?

ID	Indicator/data item	Ec-S1-R Coverage of water withdrawal costs	Ec-U1-R Economic loss due to water scarcity	Ec-U2-R Unemployment rate	Ec-U3-R Decrease in agricultural income	Ec-U4-R Water supplier financial solvency	Ec-U5-R Water supplier's ability to generate new funds to cover additional capital costs	Ec-T1-S Cost coverage of sanitation	Ec-T2-S Existence of adequate funding for treatment	Ec-T3-S Percentage of operating and maintenance costs coverage	Ec-T4-S Budget allocation for trainings and capacity development	Ec-T5-S Reliability of energy supply	Ec-T6-S Existence of a economic feasibility study	Ec-T7-S Existence of investment	Ec-T8-R Existence of government support	Ec-T9-S Generation of new funds to cover additional capital costs (e.g. by energy production)	Ec-T10-S Long-term contracts and management plans	Ec-T11-S Reliability of the used technology (security of supply/operation)	Ec-R1-S Existence of business model	Ec-R2-S Projectable permanence of (re)user in the activity	Ec-R3-S Blockage of desirable developments	Ec-R4-S Coverage of water reuse costs	Ec-R5-S Existence of (potential) market
En-S1-R	Standardised Precipitation Index (SPI 1-5 months)	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
En-S2-R	Standardised Surfaceflow Index (SSFI 3 consecutive months)	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
En-S3-R	Increase in water withdrawal		–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
En-S4-R	Percentage water resources in storage (compared to historical average)	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
En-S5-R	Existence of an emitted water scarcity decree for the area in the assessed period		–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
En-S6-R	Level of water scarcity	–		–		–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
En-S7-R	Increase in ecosystem water demand	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
En-S8-R	Decrease of biodiversity in the source area	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
En-U1-R	Irrigation efficiency	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
En-T1-S	Wastewater leakage	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
En-T2-S	Land requirement for WWTP	–	–	–	–	–	–	–		–	–	–	–	–	–	–	–	–	–	–	–	–	–
En-T3-S	Specific energy use	–	–	–	–	–	–	–	–		–		–	–	–	–	–	–	–	–	–	–	–
En-T4-S	Water losses	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
En-T5-S	Continuity of service	–	–	–	–	–	–	–	–	–	–		–	–	–	–	–	–	–	–	–	–	–
En-T6-S	Operation and maintenance aspects	–	–	–	–	–	–	–	–		–	–	–	–	–	–	–		–	–	–	–	–
En-T7-S	Existence of a technical feasibility study	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–		–	–	–	–	–
En-T8-S	Quality compliance of treated wastewater	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–		–	–	–
En-T9-S	Sludge stabilisation and safe disposal	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
En-R1-S	Water quantity reused	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–		–
En-R2-S	Compliance with agricultural irrigation use quality	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–		–	–	–

Annex F - List of Most Interlinked Indicators (MII)

Supplementary material (SM-D) of the scientific publication in Chapter 4.

Table F-1: List of MIIs. En: Environmental; Ec: Economic; So: Social: R: Risk; S: Sustainability; Intrad.: Intra-dimensional; Interd.: Inter-dimensional

Rank	Indicator ID	Dimension	Category	Interlinkages			Indicator	With data
				Intrad.	Interd.	Total		
1	En-S6-R	En	R	8	12	20	Level of water scarcity	Yes
2	So-U9-R	So	R	6	5	11	Awareness of water scarcity	No
3	So-U4-R	So	R	5	5	10	Retaining agricultural function in water-scarce conditions	Yes
4	So-U5-R	So	R	6	4	10	Retaining agricultural structure in water-scarce conditions	Yes
5	So-R2-S	So	S	5	5	10	Positive perception about water reuse	Yes
6	So-T3-S	So	S	6	3	9	Willingness to pay for sanitation and treatment	Yes
7	So-R3-S	So	S	5	4	9	Acceptance of water reuse	Yes
8	En-T8-S	En	S	5	4	9	Quality compliance of treated wastewater	Yes
9	So-U6-R	So	R	4	4	8	Controllability of impacts of water scarcity	No
10	So-U10-R	So	R	4	4	8	Perception of water scarcity	No
11	So-R4-S	So	S	5	3	8	Willingness to pay for water reuse	Yes
12	So-R5-S	So	S	5	3	8	Willingness to implement water reuse	Yes
13	Ec-T3-S	Ec	S	4	4	8	Percentage of operating and maintenance costs coverage	Yes
14	En-S5-R	En	R	1	7	8	Existence of an emitted water scarcity decree for the area in the assessed period	Yes
15	En-T5-S	En	S	3	5	8	Continuity of service	Yes
16	So-T5-S	So	S	4	3	7	Positive perception about WWT (community)	Yes
17	Ec-T2-S	Ec	S	5	2	7	Existence of adequate funding for treatment	Yes
18	En-T6-S	En	S	2	5	7	Operation and maintenance aspects	Yes
19	So-T2-S	So	S	3	3	6	Percentage of population connected to wastewater treatment	No
20	So-T4-S	So	S	5	1	6	Awareness about WWTP (community)	Yes
21	So-T6-S	So	S	3	3	6	Complaints among neighbours of WWTS	Yes

Rank	Indicator ID	Dimension	Category	Interlinkages			Indicator	With data
				Intrad.	Interd.	Total		
22	So-T7-S	So	S	2	4	6	Net employment opportunities [T]	Yes
23	Ec-U1-R	Ec	R	1	5	6	Economic loss due to water scarcity	No
24	Ec-U3-R	Ec	R	1	5	6	Decrease in agricultural income	No
25	Ec-T4-S	Ec	S	4	2	6	Budget allocation for trainings and capacity development	Yes
26	Ec-T6-S	Ec	S	6	0	6	Existence of an economic feasibility study	Yes
27	Ec-R1-S	Ec	S	4	2	6	Existence of business model	Yes
28	En-U1-R	En	R	3	3	6	Irrigation efficiency	No
29	En-T7-S	En	S	5	1	6	Existence of a technical feasibility study	No
30	So-U7-R	So	R	5	0	5	Percentage of population below poverty line	Yes
31	Ec-R2-S	Ec	S	2	3	5	Projectable permanence of (re)user in the activity	Yes
32	En-S4-R	En	R	2	3	5	Percentage water resources in storage (compared to historical average)	Yes
33	En-T2-S	En	S	3	2	5	Land requirement for WWTP	Yes
34	En-T3-S	En	S	3	2	5	Specific energy use	No
35	En-T9-S	En	S	2	3	5	Sludge stabilisation and safe disposal	No
36	En-R2-S	En	S	2	3	5	Compliance with agricultural irrigation use quality	Yes
37	So-R6-S	So	S	4	0	4	Net employment opportunities [R]	Yes
38	Ec-S1-R	Ec	R	0	4	4	Coverage of water withdrawal costs	No
39	Ec-T7-S	Ec	S	4	0	4	Existence of investment	Yes
40	Ec-T8-R	Ec	R	4	0	4	Existence of government support	Yes
41	En-S3-R	En	R	3	1	4	Increase in water withdrawal	No
42	So-U1-R	So	R	2	1	3	Percentage of access to water supply	No
43	So-U2-S	So	S	0	3	3	24-hour water supply availability	Yes
44	So-T1-S	So	S	2	1	3	Percentage of population connected to water sanitation	No
45	So-T8-S	So	S	0	3	3	Complying health and safety practices to protect workers	Yes
46	So-R1-S	So	S	3	0	3	Awareness about water reuse	Yes
47	Ec-U2-R	Ec	R	0	3	3	Unemployment rate	Yes

Rank	Indicator ID	Dimension	Category	Interlinkages			Indicator	With data
				Intrad.	Interd.	Total		
48	Ec-R4-S	Ec	S	2	1	3	Coverage of water reuse costs	Yes
49	En-S8-R	En	R	3	0	3	Decrease of biodiversity in the source area	No
50	So-U3-R	So	R	1	1	2	Dependence on agriculture for jobs	No
51	Ec-T5-S	Ec	S	0	2	2	Reliability of energy supply	Yes
52	Ec-T11-S	Ec	S	0	2	2	Reliability of the used technology (security of supply/operation)	Yes
53	Ec-R3-S	Ec	S	1	1	2	Blockage of desirable developments	Yes
54	Ec-R5-S	Ec	S	1	1	2	Existence of (potential) market	Yes
55	En-S1-R	En	R	2	0	2	Standardised Precipitation Index (SPI 1-5 months)	No
56	En-R1-S	En	S	1	1	2	Water quantity reused	Yes
57	So-U8-R	So	R	1	0	1	Human Development Index	Yes
58	Ec-T1-S	Ec	S	0	1	1	Cost coverage of sanitation	Yes
59	Ec-T9-S	Ec	S	1	0	1	Generation of new funds to cover additional capital costs (e.g., by energy production)	Yes
60	Ec-T10-S	Ec	S	0	1	1	Long-term contracts and management plans	Yes
61	En-S2-R	En	R	1	0	1	Standardised Surface flow Index (SSFI 3 consecutive months)	No
62	En-S7-R	En	R	1	0	1	Increase in ecosystem water demand	No
63	So-S1-R	So	R	0	0	0	Existence of a water resources management plan at a catchment level	No
64	Ec-U4-R	Ec	R	0	0	0	Water supplier financial solvency	Yes
65	Ec-U5-R	Ec	R	0	0	0	Water supplier's ability to generate new funds to cover additional capital costs	Yes
66	En-T1-S	En	S	0	0	0	Wastewater leakage	No
67	En-T4-S	En	S	0	0	0	Water losses	No

Annex G - List of indicators, scores, and thresholds

Supplementary material (SM-E) of the scientific publication in Chapter 4.

Table G-1: List of indicator scores

Indicator ID	Indicator	Indicator Score	Unit	Source
So-S1-R	Existence of a water resources management plan at a catchment level	ND	Yes - No	-
So-U1-R	Percentage of access to water supply	ND	%	-
So-U2-S	24-hour water supply availability	Yes	Yes - No	Interview president SSR
So-U3-R	Dependence on agriculture for jobs	ND	%	
So-U4-R	Retaining agricultural function in water-scarce conditions	Yes	Yes - No	Interview farmer
So-U5-R	Retaining agricultural structure in water-scarce conditions	Yes	Yes - No	Interview farmer
So-U6-R	Controllability of impacts of water scarcity	ND	Yes - No	-
So-U7-R	Percentage of population below poverty line	21.16	%	Communal Reports (Based on CASEN 2015)
So-U8-R	Human Development Index	0.74	-	Regional Government
So-U9-R	Awareness of water scarcity	ND	Scale 1 - 5	-
So-U10-R	Perception of water scarcity	ND	Scale 1 - 5	-
So-T1-S	Percentage of population connected to water sanitation	ND	%	-
So-T2-S	Percentage of population connected to wastewater treatment	ND	%	-
So-T3-S	Willingness to pay for sanitation and treatment	3.00	Scale 1 - 5	Interview president SSR
So-T4-S	Awareness about WWTP (community)	3.00	Scale 1 - 5	Interview president SSR
So-T5-S	Positive perception about WWT (community)	4.00	Scale 1 - 5	Interview president SSR
So-T6-S	Complaints among neighbours of WWTS	No	Yes - No	Interview president SSR
So-T7-S	Net employment opportunities [T]	0	-	Interview president SSR
So-T8-S	Complying health and safety practices to protect workers	Yes	Yes - No	Interview president SSR
So-R1-S	Awareness about water reuse	2.00	Scale 1 - 5	Interview president SSR
So-R2-S	Positive perception about water reuse	4.00	Scale 1 - 5	Interview president SSR
So-R3-S	Acceptance of water reuse	4.00	Scale 1 - 5	Interview president SSR

Indicator ID	Indicator	Indicator Score	Unit	Source
So-R4-S	Willingness to pay for water reuse	4.00	Scale 1 - 5	Interview president SSR
So-R5-S	Willingness to implement water reuse	4.00	Scale 1 - 5	Interview president SSR
So-R6-S	Net employment opportunities [R]	0	-	Interview president SSR
Ec-S1-R	Coverage of water withdrawal costs	ND	%	-
Ec-U1-R	Economic loss due to water scarcity	ND	USD/year	-
Ec-U2-R	Unemployment rate	7.10	%	National Institute of Statistics (Boletín Estadístico 2019: Región de Coquimbo)
Ec-U3-R	Decrease in agricultural income	ND	USD/year	-
Ec-U4-R	Water supplier financial solvency	100	%	Interview president SSR
Ec-U5-R	Water supplier's ability to generate new funds to cover additional capital costs	Yes	Yes - No	Interview president SSR
Ec-T1-S	Cost coverage of sanitation	100	%	Interview president SSR
Ec-T2-S	Existence of adequate funding for treatment	Yes	Yes - No	Interview president SSR
Ec-T3-S	Percentage of operating and maintenance costs coverage	100	%	Interview president SSR
Ec-T4-S	Budget allocation for trainings and capacity development	Yes	Yes - No	Interview president SSR
Ec-T5-S	Reliability of energy supply	Yes	Yes - No	Interview president SSR
Ec-T6-S	Existence of an economic feasibility study	Yes	Yes - No	Fundación Chile
Ec-T7-S	Existence of investment	Yes	Yes - No	Interview president SSR
Ec-T8-R	Existence of government support	Yes	Yes - No	Interview president SSR
Ec-T9-S	Generation of new funds to cover additional capital costs (e.g., by energy production)	No	Yes - No	Interview president SSR
Ec-T10-S	Long-term contracts and management plans	4.00	Scale 1 - 5	Interview president SSR
Ec-T11-S	Reliability of the used technology (security of supply/operation)	4.00	Scale 1 - 5	Interview president SSR
Ec-R1-S	Existence of business model	Yes	Yes - No	Interview president SSR
Ec-R2-S	Projectable permanence of (re)user in the activity	Yes	Yes - No	Interview president SSR
Ec-R3-S	Blockage of desirable developments	No	Yes - No	Interview president SSR
Ec-R4-S	Coverage of water reuse costs	100	%	Interview president SSR
Ec-R5-S	Existence of (potential) market	Yes	Yes - No	Interview president SSR
En-S1-R	Standardised Precipitation Index (SPI 1-5 months)	ND	-	

Indicator ID	Indicator	Indicator Score	Unit	Source
En-S2-R	Standardised Surface flow Index (SSFI 3 consecutive months)	ND	-	-
En-S3-R	Increase in water withdrawal	ND	%	-
En-S4-R	Percentage water resources in storage (compared to historical average)	100.00	%	DGA - Boletin 498 Oct. 2019
En-S5-R	Existence of an emitted water scarcity decree for the area in the assessed period	Yes	Yes - No	DGA - Decretos Zonas Escasez Historico
En-S6-R	Level of water scarcity	0.87	-	Recoleta reservoir
En-S7-R	Increase in ecosystem water demand	ND	%	-
En-S8-R	Decrease of biodiversity in the source area	ND	%	-
En-U1-R	Irrigation efficiency	ND	%	-
En-T1-S	Wastewater leakage	ND	%	-
En-T2-S	Land requirement for WWTP	0.28	m2/inhab	Fundación Chile
En-T3-S	Specific energy use	ND	kWh/m3	-
En-T4-S	Water losses	ND	%	-
En-T5-S	Continuity of service	5.00	Scale 1 - 5	Interview with president of SSR
En-T6-S	Operation and maintenance aspects	3.00	Scale 1 - 5	Interview with president of SSR
En-T7-S	Existence of a technical feasibility study	ND	Yes - No	-
En-T8-S	Quality compliance of treated wastewater	Yes	Yes - No	Interview with president of SSR / Fundación Chile
En-T9-S	Sludge stabilisation and safe disposal	ND	Yes - No	-
En-R1-S	Water quantity reused	100	%	Interview with president of SSR/farmer
En-R2-S	Compliance with agricultural irrigation use quality	Yes	Yes - No	Interview with president of SSR / Fundación Chile

Table G-2: List of thresholds and evaluation results. Evaluation categories G: Green, R: Red, Y: Yellow.

Indicator ID	Indicator	Indicator Score	Unit	Red (Lower limit)	Yellow	Green (Upper Limit)	Source	Evaluation
So-S1-R	Existence of a water resources management plan at a catchment level	ND	Yes - No	-	-	-	-	-
So-U1-R	Percentage of access to water supply	ND	%	-	-	-	-	-
So-U2-S	24-hour water supply availability	Yes	Yes - No	No	-	Yes	Defined by authors	G
So-U3-R	Dependence on agriculture for jobs	ND	%	-	-	-	-	-
So-U4-R	Retaining agricultural function in water-scarce conditions	Yes	Yes - No	No	-	Yes	Defined by authors	G
So-U5-R	Retaining agricultural structure in water-scarce conditions	Yes	Yes - No	No	-	Yes	Defined by authors	G
So-U6-R	Controllability of impacts of water scarcity	ND	Yes - No	-	-	-	-	-
So-U7-R	Percentage of population below poverty line	21.16	%	[66.67 - 100]	[33.33 - 66.67[	[0 - 33.33[	Defined by authors	R
So-U8-R	Human Development Index	0.74	-	[0 - 0.33[	[0.33 - 0.67[	[0.67 - 1.00]	Defined by authors	G
So-U9-R	Awareness of water scarcity	ND	Scale 1 - 5	-	-	-	-	-
So-U10-R	Perception of water scarcity	ND	Scale 1 - 5	-	-	-	-	-
So-T1-S	Percentage of population connected to water sanitation	ND	%	-	-	-	-	-
So-T2-S	Percentage of population connected to wastewater treatment	ND	%	-	-	-	-	-
So-T3-S	Willingness to pay for sanitaton and treatment	3.00	Scale 1 - 5	[1.00 - 2.33[	[2.33 - 3.67[	[3.67 - 5.00]	Defined by authors	Y
So-T4-S	Awareness about WWTP (community)	3.00	Scale 1 - 5	[1.00 - 2.33[	[2.33 - 3.67[	[3.67 - 5.00]	Defined by authors	Y
So-T5-S	Positive perception about WWT (community)	4.00	Scale 1 - 5	[1.00 - 2.33[	[2.33 - 3.67[	[3.67 - 5.00]	Defined by authors	G
So-T6-S	Complaints among neighbours of WWTS	No	Yes - No	Yes	-	No	Defined by authors	G
So-T7-S	Net employment opportunities [T]	0	-	<0	0	>0	Defined by authors	Y
So-T8-S	Complying health and safety practices to protect workers	Yes	Yes - No	No	-	Yes	Defined by authors	G
So-R1-S	Awareness about water reuse	2.00	Scale 1 - 5	[1.00 - 2.33[	[2.33 - 3.67[	[3.67 - 5.00]	Defined by authors	R
So-R2-S	Positive perception about water reuse	4.00	Scale 1 - 5	[1.00 - 2.33[	[2.33 - 3.67[	[3.67 - 5.00]	Defined by authors	G
So-R3-S	Acceptance of water reuse	4.00	Scale 1 - 5	[1.00 - 2.33[	[2.33 - 3.67[	[3.67 - 5.00]	Defined by authors	G
So-R4-S	Willingness to pay for water reuse	4.00	Scale 1 - 5	[1.00 - 2.33[	[2.33 - 3.67[	[3.67 - 5.00]	Defined by authors	G
So-R5-S	Willingness to implement water reuse	4.00	Scale 1 - 5	[1.00 - 2.33[	[2.33 - 3.67[	[3.67 - 5.00]	Defined by authors	G

Indicator ID	Indicator	Indicator Score	Unit	Red (Lower limit)	Yellow	Green (Upper Limit)	Source	Evaluation
So-R6-S	Net employment opportunities [R]	0	-	<0	0	>0	Defined by authors	Y
Ec-S1-R	Coverage of water withdrawal costs	ND	%	-	-	-	-	-
Ec-U1-R	Economic loss due to water scarcity	ND	USD/year	-	-	-	-	-
Ec-U2-R	Unemployment rate	7.10	%	[66.67 - 100]	[33.33 - 66.67[	[0.00 - 33.33[	Research team (based on the main goal of policy making - see ILO)	G
Ec-U3-R	Decrease in agricultural income	ND	USD/year	-	-	-	-	-
Ec-U4-R	Water supplier financial solvency	100	%	[0.00 - 33.33[	[33.33 - 66.67[	[66.67 - 100]	Defined by authors	G
Ec-U5-R	Water supplier's ability to generate new funds to cover additional capital costs	Yes	Yes - No	No	-	Yes	Defined by authors	G
Ec-T1-S	Cost coverage of sanitation	100	%	[0.00 - 33.33[	[33.33 - 66.67[	[66.67 - 100]	Defined by authors	G
Ec-T2-S	Existence of adequate funding for treatment	Yes	Yes - No	No	-	Yes	Defined by authors	G
Ec-T3-S	Percentage of operating and maintenance costs coverage	100	%	[0.00 - 33.33[	[33.33 - 66.67[	[66.67 - 100]	Defined by authors	G
Ec-T4-S	Budget allocation for trainings and capacity development	Yes	Yes - No	No	-	Yes	Defined by authors	G
Ec-T5-S	Reliability of energy supply	Yes	Yes - No	No	-	Yes	Defined by authors	G
Ec-T6-S	Existence of an economic feasibility study	Yes	Yes - No	No	-	Yes	Defined by authors	G
Ec-T7-S	Existence of investment	Yes	Yes - No	No	-	Yes	Defined by authors	G
Ec-T8-R	Existence of government support	Yes	Yes - No	No	-	Yes	Defined by authors	G
Ec-T9-S	Generation of new funds to cover additional capital costs (e.g., by energy production)	No	Yes - No	No	-	Yes	Defined by authors	R
Ec-T10-S	Long-term contracts and management plans	4.00	Scale 1 - 5	[1.00 - 2.33[	[2.33 - 3.67[	[3.67 - 5.00]	Defined by authors	G
Ec-T11-S	Reliability of the used technology (security of supply/operation)	4.00	Scale 1 - 5	[1.00 - 2.33[	[2.33 - 3.67[	[3.67 - 5.00]	Defined by authors	G
Ec-R1-S	Existence of business model	Yes	Yes - No	No	-	Yes	Defined by authors	G
Ec-R2-S	Projectable permanence of (re)user in the activity	Yes	Yes - No	No	-	Yes	Defined by authors	G
Ec-R3-S	Blockage of desirable developments	No	Yes - No	Yes	-	No	Defined by authors	G
Ec-R4-S	Coverage of water reuse costs	100	%	[0.00 - 33.33[	[33.33 - 66.67[	[66.67 - 100]	Defined by authors	G
Ec-R5-S	Existence of (potential) market	Yes	Yes - No	No	-	Yes	Defined by authors	G

Indicator ID	Indicator	Indicator Score	Unit	Red (Lower limit)	Yellow	Green (Upper Limit)	Source	Evaluation
En-S1-R	Standardised Precipitation Index (SPI 1-5 months)	ND	-	-	-	-	-	-
En-S2-R	Standardised Surface flow Index (SSFI 3 consecutive months)	ND	-	-	-	-	-	-
En-S3-R	Increase in water withdrawal	ND	%	-	-	-	-	-
En-S4-R	Percentage water resources in storage (compared to historical average)	100.00	%	< 60	≥ 60 and < 80	≥ 80	2012_DGA-Res1674	G
En-S5-R	Existence of an emitted water scarcity decree for the area in the assessed period	Yes	Yes - No	Yes	-	No	Defined by authors	R
En-S6-R	Level of water scarcity	0.87	-	[0.00 - 33.33[	[33.33 - 66.67[	[66.67 - 100]	Defined by authors (based on Veldkamp et al. 2016/Kummu et al. 2010)	G
En-S7-R	Increase in ecosystem water demand	ND	%	-	-	-	-	-
En-S8-R	Decrease of biodiversity in the source area	ND	%	-	-	-	-	-
En-U1-R	Irrigation efficiency	ND	%	-	-	-	-	-
En-T1-S	Wastewater leakage	ND	%	-	-	-	-	-
En-T2-S	Land requirement for WWTP	0.28	m2/inhab	<0.10 or >0.30	[0.10-0.12[or]0.25-0.30]	[0.12 - 0.25]	WHO guidelines for SUWA - Vol. 2 Table 9.1	Y
En-T3-S	Specific energy use	ND	kWh/m3	-	-	-	-	-
En-T4-S	Water losses	ND	%	-	-	-	-	-
En-T5-S	Continuity of service	5.00	Scale 1 - 5	[1.00 - 2.33[	[2.33 - 3.67[	[3.67 - 5.00]	Defined by authors	G
En-T6-S	Operation and maintenance aspects	3.00	Scale 1 - 5	[3.67 - 5.00]	[2.33 - 3.67[	[1.00 - 2.33[	Defined by authors	Y
En-T7-S	Existence of a technical feasibility study	ND	Yes - No	-	-	-	-	-
En-T8-S	Quality compliance of treated wastewater	Yes	Yes - No	No	-	Yes	DS 90/2000	G
En-T9-S	Sludge stabilisation and safe disposal	ND	Yes - No	-	-	-	-	-
En-R1-S	Water quantity reused	100	%	[0.00 - 33.33[	[33.33 - 66.67[	[66.67 - 100]	Defined by authors	G
En-R2-S	Compliance with agricultural irrigation use quality	Yes	Yes - No	No	-	Yes	DS 90/2000	G