Measurement and assessment of Circular Economy in water systems

A thesis submitted for the degree of Doctor of Philosophy

by

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Dedicated to Aris Karaleftheris

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Abstract

As the concept of Circular Economy (CE) is gaining momentum, the need for appropriate circularity assessment methodologies and indicators grows exponentially. Although circularity in water requires a nexus approach according to the new Circular Economy Action Plan, a sectoral division is still dominated in the scientific community. In this study, a thorough appraisal of the latest literature is conducted, providing an overview of existing tools, methodologies and indicators that have been used to assess water systems considering the need of assessing both anthropogenic and natural elements. The identified lack of a holistic methodology and comprehensive indicators assessing complete water systems from a circularity perspective led to the development of a circularity assessment framework, namely the Multi-Sectoral Water Circularity Assessment (MSWCA) framework. The MSWCA follows a multi-sectoral systems approach, symbiotically managing key socio-economic and non-economic sectors of the Water-Energy-Food-Ecosystems nexus. The developed framework enables the investigation of the feedback loops between the nature-managed and human-managed systems to assess water and water-related resources circularity and develops an indicators database facilitating the assessment. This study further develops a novel approach that combines both expert and participatory practices for the prioritization of indicators based on views and needs of practitioners, whilst considering the complex interdependencies of the indicators and determining their importance. The 20 circularity indicators of the MSWCA framework are ranked by different stakeholders and their interrelationships are identified using the Interpretive Structural Model, resulting in 6 levels of importance. Cross-impact matrix multiplication applied to classification (MICMAC) analysis further enabled the classification of the indicators into 4 categories based on their driving and dependence power. Finally, following the MSWCA framework, a dynamic indicators-based modelling tool is developed and applied to the HYDROUSA H2020 project. Benchmark and dynamic circularity assessments are performed to compare the circularity performance of the HYDRO system to the previous configuration of the system and to optimize HYDRO system's operation by investigating changes in circularity performance of different operational scenarios, respectively. The circularity performance of the system is based on the results of 46 operational indicators that target system's multi-functionality and additional benefits and costs, all incorporated resources, waste and emissions, as well as economic, technical and ecological aspects, the 3 CE principles and are related to 13 SDGs.

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List of Abbreviations

AGF	Agroforestry
AOI	Action-Oriented Indicator
BCR	Benefit Cost Ratio
BOD	Biochemical Oxygen Demand
C	Carbon
CAPEX	Capital Expenditure
CBA	Cost-Benefit Analysis
CCF	Circular Carbon Flow
CChF	Circular Chemicals Flow
CCI	Circular Carbon Inflow
CCO	Circular Carbon Outflow
CE	Circular Economy
CEA	Cost-Effectiveness Analysis
CEIP	Circular Economy Indicator Prototype
CET	Circular Economy Toolkit
CF	Carbon Footprint
CFA	Carbon Footprint Accounting
ChI	Chemicals use Intensity
CHP	Combined Heat & Power
CI	Circular Index
CNF	Circular Nitrogen Flow
CNI	Circular Nitrogen Inflow
CNO	Circular Nitrogen Outflow
COD	Chemical Oxygen Demand
COMF	Circular Organic Materials Flow
CPF	Circular Phosphorus Flow
CPI	Circularity Performance Indicator
CPI	Circular Phosphorus Inflow
CPO	Circular Phosphorus Outflow
CU	Circular Use
CVM	Contingent Valuation Method
CW	Constructed Wetlands
CWF	Circular Water Flow
CWI	Circular Water Inflow
CWO	Circular Water Outflow
DOI	Data-Oriented Indicator
DONE	Design Out Negative Externalities
DWTP	Drinking Water Treatment Plant
EbA	Ecosystem-based Adaptation
EDM	Energy Demand Minimization
EEI	Emission Eco-efficiency Index
ELC	Extended Life of Carbon

ELN	Extended Life of Nitrogen
ELP	Extended Life of Phosphorus
ELW	Extended Life of Water
EPE	Energy Production Efficiency
ERC	Environmental and Resource Cost
ES	Ecosystem Services
ESS	Energy Self-Sufficiency
EUI	Emission Utilization Index
FRC	Full Recovery Cost
GHG	Greenhouse Gas
GI	Green Infrastructure
GIS	Geographic Information System
GNLR	Green Land Recycling
GNS	Gross Nitrogen Surplus
GRLR	Grey Land Recycling
H2HA	Harvest to Harvest Approach
IAS	Individual Appropriate Systems
ICR	Intrinsic Circularity Revenues
ICS	Intrinsic Circularity Savings
IEM	Integrated Environmental Model
IOI	Information-Oriented Indicator
ISM	Interpretive Structural Model
KRU	Keep Resources in Use
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCCA	Life Cycle Cost Analysis
LD	Land Densification
LR	Lost Revenues
LULC	Land use land cover
MCA	Multi-criteria Analysis
MCI	Material Circularity Indicator
MFA	Material Flow Analysis
MFCA	Material Flow Cost Accounting
MICMAC	Cross-impact matrix multiplication applied to classification
MSA	Multi-Sectoral Systems Analysis
MSWCA	Multi-Sectoral Water Circularity Assessment
N	Nitrogen
NBS	Nature-based Solutions
NHP	Natural Hydrological Performance
NMI	New Materials Intensity
NPV	Net Present Value
NRNMI	Non-Renewable Materials Intensity
OPEX	Operating Expenses
P	Phosphorus
PP	Payback Period

RM	Reachability Matrix
RMI	Recycled Materials Intensity
RNE	Regeneration of Natural Environment
RNMI	Renewable Materials Intensity
RSA	Regionalized Sensitivity Analysis
RUMI	Reused/Repurposed Materials Intensity
SDGs	Sustainable Development Goals
SEM	Structural Equation Modelling
SFA	Substance Flow Analysis
SS	Suspended Solids
SSIM	Structural Self-Interaction Matrix
SuDS	Sustainable Drainage Systems
SWB	Soil Water Balance
SWE	System's Water Efficiency
TM	Territorial Metabolism
TR	Total Revenues
UASB	Upflow Anaerobic Sludge Blanket
UF	Ultrafiltration
UHA	Urban Harvest Approach
UV	Ultraviolet
UWM	Urban Water Metabolism
UWWTD	Urban Wastewater Treatment Directive
WDM	Water Demand Minimization
WEFE	Water-Energy-Food-Ecosystems
WEI	Waste Eco-efficiency Index
WSUD	Water Sensitive Urban Design
WTA	Willingness to Accept
WTP	Willingness to Pay
WUI	Waste Utilization Index
WWR	Water Withdrawal Reduction
WWTP	Wastewater Treatment Plant

1. Introduction

1.1 Research Motivation

The conventional unidirectional model of society and economy, centred around endless economic growth and development, is characterized by pronounced resource scarcity, excessive waste and pollution loads (Katsou et al., 2020). This linear model, or linear economy, is acknowledged of being culpable of some of the most pressing global challenges (e.g. social inequalities, climate change, wealth concentration and value lost) (Ajwani-Ramchandani et al., 2021). A response to the root cause of these cross-cutting challenges can be found in the emerging concept of Circular Economy (CE) (Ghisellini et al., 2016). Although there is not a unique and widely accepted definition (Kirchherr et al., 2017; Friant et al., 2020), CE can be seen as a systemic approach to development that is regenerative by design, benefits society, businesses and the environment and aims to decouple growth from the imprudent consumption of finite resources and eliminate waste (EMF, 2017a).

The concept of CE receives tremendous traction and shapes political agendas worldwide. For example, with the European Green Deal (EC, 2019a), the Commission placed at the centre of its priorities the need to take immediate actions to fight climate change and make Europe climate-neutral by 2050. CE is a key strategy in achieving the goals of the European Green Deal. In March 2020 the new Circular Economy Action Plan (CEAP) (EC, 2020) provided a future-oriented agenda for systemic, deep and transformative transition to CE, able to make circularity working for people, regions and cities. In the new CEAP, water together with food and nutrients is one of the seven key value chains requiring urgent, comprehensive and coordinated circularity actions. Since the first CEAP (EC, 2015a), in which water was not part of the identified priority areas, the Commission acknowledges that the different sectors have specific CE challenges, resulting from their inherent specificities, environmental impacts, and materials dependence. Circularity approaches need to ensure a systems thinking by accounting for the "interactions between the various phases of the cycle along the whole value chain", considering the sector-specific challenges.

An initial comparison between water and the key value chains of the new CEAP indicates significant differences, potentially affecting the specific challenges and water circularity approach. First, all six priority areas follow a sectoral approach, whereas water is considered as part of a nexus. In a resource nexus, numerous factors and functional elements need to be considered (Serrano-Tovar et al., 2019), leading to additional interactions that need to be investigated, which further increases the complexity of implementing, measuring and assessing circularity.

The second distinction can be found in the cycle of the value chain. On one hand, in the six identified priority areas, natural resources – in many cases these are finite resources – are extracted from natural reserves. In most of the cases these natural resources cannot be used in their native form. Thus, they are processed to produce raw materials that have different properties from the initial natural resources are used to create the final product. The value chain of such products is therefore, explicitly restricted to the technosphere, since there are no anthropogenic actions that could increase the natural reserves of the required materials or resources, nor could they ever enhance their natural cycle, which is based on geological processes that span millions of years (Höök, 2013). In such products, sectors and value chains, the focus seems to be on actions that would keep materials and products in use, as well as maintain their value for as long as possible (Sharma et al., 2021). Such actions are based on the R’s waste hierarchy (e.g. recover, reuse, repair, remanufacture, recycle) that can extend the useful life of products (Kühl et al., 2018). Product sharing (He et al., 2021) and product-as-a-service (Han et al., 2020) include some additional approaches and business models to CE. In literature, such actions are defined as intrinsic circularity (Saidani et al., 2019). However, various scholars highlight the need to further measure and evaluate consequential circularity, in an effort to consider environmental and probably social impacts of circularity actions (Kirchherr et al., 2017; Linder et al., 2017).

On the other hand, a water value chain restricted to actions considering only the technosphere is questioned in this study as water in its native form is perpetually transferred between and interferes with the natural and the anthropogenic system (National Academies of Sciences, Engineering, and Medicine, 2018). Therefore, restricted actions focusing on the human-managed system would isolate water from its wider system and consequently, any claim related to “systems thinking” – mandated by CE – would not be accurate. Additionally, an isolated approach to water circularity would inevitably result in limited CE solutions and measures. Since water is a non-substitutable commodity (i.e. there are no other natural or human-made commodity that can replace water; Yang et al., 2021), circular solutions following an isolated approach would be solely targeted at water recycling and reuse (e.g. agricultural and industrial water), and water use or demand reduction.

Considering the complete water system, water strongly depends on the natural water cycle for its renewal and the hydrological cycle is being disrupted by numerous direct (e.g. water diversion, increased soil sealing) and indirect (e.g. significantly reduced biodiversity) causes. The natural water cycle plays a key role in the self-regulation of planetary temperatures (Nordstrom et al., 2005), and interacts with microbial activity, carbon and nutrients cycling, edaphic conditions, and vegetation productivity, dynamics and diversity (Jouquet et al., 2006). Ecosystem functioning is sustained by these natural feedback loops. Due to this feedback mechanism of the ecosystems, any change will inevitably result in a ripple effect, affecting either in the long or short term all the natural system's components (Ward et al., 2018), and consequently the anthropogenic system as well. To this extent, a fragmented approach to water circularity management and evaluation would potentially hide the risk of burden shifting and is unlikely to solve complex environmental problems.

Following a systems approach to circularity in water creates an opportunity to address not only water-related issues, but also cross-cutting challenges such as biodiversity loss, soil fertility, climate change. Such a holistic and systemic approach further highlights the importance of water infrastructure as an integral part of the water value chain and more precisely the combination of grey and green components, such as nature-based solutions (NBS) (Cohen-Shacham et al., 2016). The multi-functionality and the fact that nature is integral part to the solution in NBS create a unique feature of combining water circularity and NBS – i.e. "Design Water In" – compared to the current linear approach, which is characterised by superimposing solutions to nature and by removing water from natural systems, i.e. "Design Water Out" (O'Hogain and McCarton, 2018). This transformative change would potentially play a key role in circularity in water systems.

At present there is a limited available literature approaching the concept of CE in water from a systemic and holistic point of view, which evidently increases the complexity of measuring and assessing CE in water. Three reports published by corporate bodies (i.e. Stuchtey, 2015; IWA, 2016; Arup et al., 2018) develop similar conceptual frameworks on the role of water in CE. Although these conceptual frameworks enable a better understanding of the topic, they lack operationalization and insights on how to measure and assess circularity in water systems. On the other hand, the scientific community mainly focuses on the role of wastewater treatment plants (WWTPs) in CE (e.g. Wang et al., 2018; Kehrein et al., 2020), on assessing specific technologies from a circularity perspective (e.g. Husgafvel et al., 2016), and on resource recovery in industrial symbiosis (e.g. Dai et al., 2011; Yang, 2012; Jaria et al., 2017). However, integrated or nexus approaches to deal with interdisciplinary issues are increasingly acknowledged in the recent literature (e.g. Li et al., 2018; Paiho et al., 2020; Nguyen et al., 2020) but they do not specifically focus on both water and CE. Therefore, this thesis aims to redefine the positioning of water within the concept of CE and to develop a holistic and systemic water circularity assessment methodology, covering all the important aspects of water circularity facilitating informed decision-making.

1.2 Overview of research program

1.2.1 Research questions addressed by this thesis

The primary research questions (RQ) that will be addressed in this thesis are:

- What needs to be measured in order to assess circularity in water systems? What is the state-of-the-art in methodologies, tools and indicators that can be used to holistically measure and assess circularity of complex water systems? (Chapter 2).
- What are the guidelines that need to be followed and the tasks that need to be performed in order to develop a methodology that holistically measures and assesses circularity performance of water systems? (Chapter 3).
- How can different visions and needs of practitioners be combined with scientific knowledge into a comprehensive methodology to result in a set of appropriate and accepted circularity indicators? (Chapter 4).
- What aspects need to be considered to select appropriate indicators for holistically measuring and assessing circularity and sustainability of specific case studies? What are the different types of circularity assessment that can be used and what are the different insights and information that can be gained from each of them? (Chapter 1).

1.2.2 Aim and objectives

Research hypothesis: *The existing circularity approaches developed to evaluate different system levels following a sectoral approach and focusing mostly on techno-economic aspects are not directly applicable to water systems as they fail to consider water-related specificities. Water is an undervalued public good that cannot be manufactured or replaced, intersects with* *all socio-economic sectors requiring a nexus approach, has a regional nature and its renewability strongly depends on the local conditions and the natural water cycle.*

The aim of the current research is to develop a methodological assessment framework that would integrate widely accepted methodologies and existing indicators to evaluate circularity in complex water systems, considering their numerous particularities compared to other systems. The developed methodological assessment framework needs to follow a systemic and holistic approach, effectively targeting the principles of CE, coupling human-managed and nature-managed systems, symbiotically managing the various incorporated resources, covering environmental, social, and economic aspects, and being in line with the SDGs. In order to enable a better understanding of the develop framework, as well as to test its operationalization that would promote its application and future adoption, it is applied in a real case study developed with the HYDROUSA H2020 project. The outcome of this research is expected to shed light on how to better measure and assess circularity of complex water systems, what type of assessment is required for different evaluation purposes, how to select appropriate circularity performance indicators in a systematic manner and how to engage the relevant stakeholders to participate in the indicators selection process. These outcomes would enable decision-making on system's improvement from a circularity and sustainability point of view, based on multifarious information that is effectively communicated.

To achieve the aim of this research, the specific objectives of this thesis are to:

- Review existing literature on the topic of circularity in water systems and how natural, semi-natural and anthropogenic components of water systems are currently assessed. This investigation will enhance the understanding on the advantages, disadvantages and current gaps of existing tools, methodologies and indicators to assess circularity in water systems.

- Build consensus on what is a suitable approach to circularity assessment of water systems by investigating circularity prerequisites and the intrinsic nature of water systems. The outcome of this investigation is used to develop a methodological framework to assess circularity in water systems. The latter combined with the outcome of the first objective will result in a structural approach for integrating appropriate methods and tools, obtaining required data and using comprehensive circularity indicators.

- Develop a participatory approach that combines scientific knowledge and views of various stakeholders to facilitate the prioritization of circularity indicators. The outcome will enable the classification of appropriate indicators by considering both the needs of industrial stakeholders and the importance level of indicators deriving from their interrelationships. The developed approach should be versatile and applicable to various sets of indicators.

- Implement the methodological assessment framework in a real case study to provide a systematic methodology that enables an indicators selection process based on scientific knowledge, robust criteria and specificities of the system, and to investigate the different types of assessment that are required to aid the comparison between new and reference systems and to improve the system's operation based on its circularity performance. The outcome of this research will enable decision-making on strategic interventions for improving circularity in water systems.

1.2.3 Methodological approach

In the first part of the thesis, a thorough review of the available knowledge on i) CE, ii) CE in water, iii) CE assessment methodologies and indicators, iv) NBS as enablers to CE in water systems, v) assessment methodologies and existing indicators for evaluating NBS in water systems, vi) assessment methodologies and existing indicators for evaluating complete water systems, and vii) complexities and intrinsic nature of water systems is conducted. The review is based on a narrative literature review (Chapter 2). The knowledge obtained is then integrated into the development of a holistic methodological assessment framework to systemically evaluate circularity in complex water systems. The framework explains the approach to circularity, the methodological process for the assessment, the required methods and tools that need to be integrated into a single assessment model, its uncertainty, the data requirements and indicators to communicate the assessment results (Chapter 3).

The second part of the research investigates the practical applicability of circularity assessment methodology and indicators. In the first phase of the second part, a dynamic participatory approach is developed to enable the prioritization of circularity indicators considering both scientific knowledge and practical needs of the industry. For this purpose, thorough questionnaires and workshops were conducted, asking various industrial stakeholders, decision-makers and academics to rank pre-selected circularity performance indicators (i.e. circularity indicators included within the developed framework). The ranked indicators were then analysed based on their interrelationships, using experts opinion, and an Interpretive Structural Model was developed, resulting in six levels of indicators' importance. MICMAC analysis was further deployed, enabling the classification of the indicators into four categories based on their driving and dependence power (Chapter 4).

In Chapter 5 the guidelines of the Multi-Sectoral Water Circularity Assessment (MSWCA) framework developed in Chapter 3 are followed to develop and implement a dynamic indicators-based modelling methodology that measures and assesses circularity of systems under the Water-Energy-Food-Ecosystems nexus. This part provides a systematic methodology that enables an indicators selection process based on system's multi-functionality, on 6 circularity categories (i.e. water, energy, resources, waste and emissions, economic and other), on the 3 CE principles, and the 17 Sustainable Development Goals (SDGs). A further differentiation between benchmark and dynamic assessment is made, with the latter targeting the investigation of dynamic interdependencies between system's components that enable the development of scenarios for aiding system's operation based on the circularity performance. The developed methodology is implemented in a real case study developed within the HYDROUSA H2020 project.

The methodological process of this thesis is further depicted in Figure 1.1.

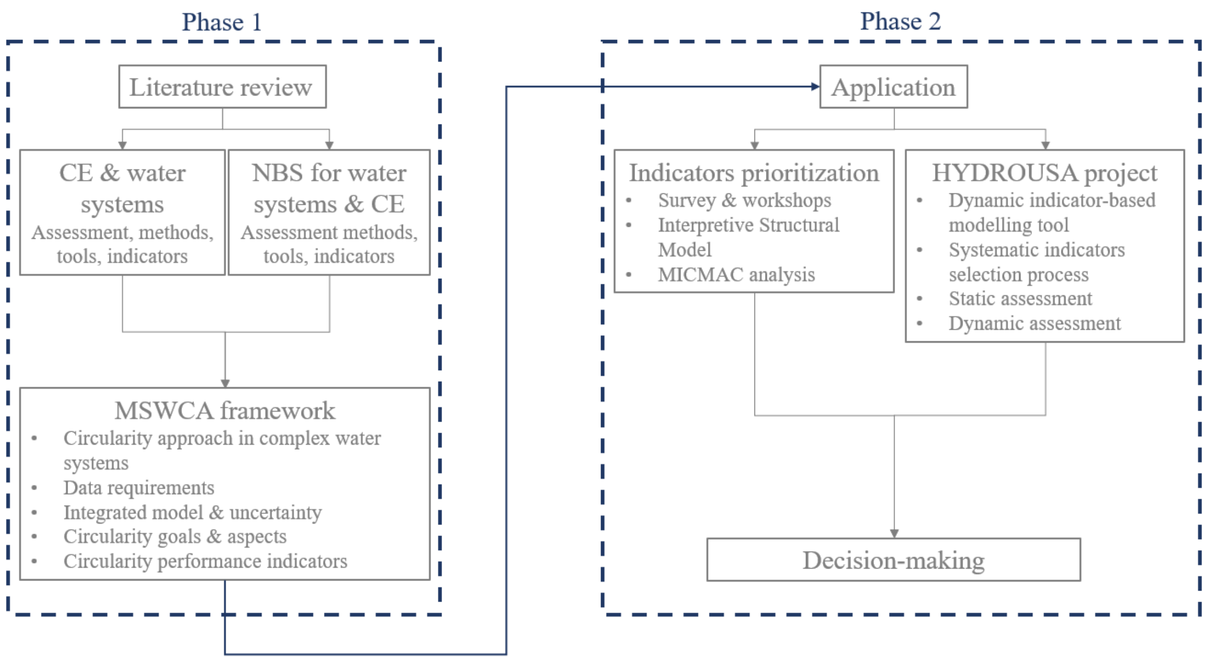


Figure 1.1: Methodological process applied in the thesis

1.2.4 Thesis outline

Figure 1.2 summarises the main objectives of each chapter and how information extracted from each chapter is used in the subsequent analysis.

Chapter 2: Literature review – Nature-based solutions as enablers of circularity in water systems: A review on assessment methodologies, tools and indicators

In this chapter, a literature review is conducted to investigate existing tools, methodologies and indicators that have been used to assess NBS for water management, as well as complete water systems considering the need of assessing both anthropogenic and natural elements. NBS are considered as integral components of circular water systems that connect human-managed to nature-managed systems. Furthermore, facilitators and barriers with respect to existing policies and regulations on NBS and circularity are identified. Advantages, disadvantages and current gaps of existing tools, methods and indicators related to circularity assessment of water systems are identified and reported.

Chapter 3: Water Cycle and Circular Economy: Developing a Circularity Assessment Framework for Complex Water Systems

This chapter investigates the various particularities of complex water systems from a circularity perspective and identifies water circularity assessment prerequisites. Based on these considerations a game changing circularity assessment framework (i.e. the MSWCA framework) is developed that provides guidelines for multi-sectoral systems assessment following a systemic, holistic and territorial approach. The framework considers various water-related socio-economic sectors, the feedback loops between technosphere and biosphere and targets the symbiotic management of water and water-related resources. The framework further develops an indicators database that includes all the relevant data requirements, as well as existing and newly developed indicators assessing systems' circularity based on the achievement of the three CE principles and the consideration of various aspects (e.g. physical, economic, environmental, etc.). Limitations of the developed framework are also reported.

Chapter 4: Validating Circular Performance Indicators: The interface between Circular Economy and Stakeholders

This chapter builds upon the work undertaken in Chapter 3 and focuses on the development and application of appropriate CE indicators as an issue that concerns both the scientific and the business community, as well as decision makers. The existing gap between research, policy and practice could be bridged by using a dynamic indicators selection approach that combines both expert and participatory practices. This chapter develops such a novel approach for the selection of indicators based on views and needs of practitioners, whilst considering the complex interdependencies of the indicators and determining their importance. The twenty circularity performance indicators of the MSWCA database are used and ranked by different stakeholders. The interrelationships of the indicators are identified using the Interpretive Structural Model, resulting in the identification of their importance level and a cross-impact matrix multiplication applied to classification (MICMAC) analysis is further deployed, enabling the classification of indicators into four categories based on their driving and dependence power.

Chapter 5: Assessing circularity of multi-sectoral systems under the Water-Energy-Food-Ecosystems (WEFE) nexus

This Chapter follows the guidelines of the MSWCA framework to develop and implement a dynamic indicators-based assessment model that measures and evaluates circularity and sustainability of systems under the Water-Energy-Food-Ecosystems nexus. The ex-post assessment is differentiated between benchmark and dynamic assessment, both of which are based on the modelling results communicated using selected circularity performance indicators. A systematic methodology is developed that enables the indicators selection process based on system's multi-functionality, on 6 circularity categories (i.e. water, energy, resources, waste and emissions, economic and other), on the 3 CE principles, and the 17 Sustainable Development Goals (SDGs). After the selection of appropriate indicators for the assessment and their integration into the developed model, different simulations are performed to obtain the circularity performance of the new system under the current operational conditions, under alternative operational conditions, and of a reference system. A comparison between the reference system and the new system under current operational conditions is performed using static assessment. Dynamic assessment is performed using sensitivity analysis that enables the identification of the operational parameters that influence the circularity performance of the system the most. Dynamic assessment is used to improve system's operation based on its circularity and sustainability performance. The developed tool is applied in the HYDROUSA H2020 project to enable a better understanding of the circularity assessment process and facilitate decision-making.

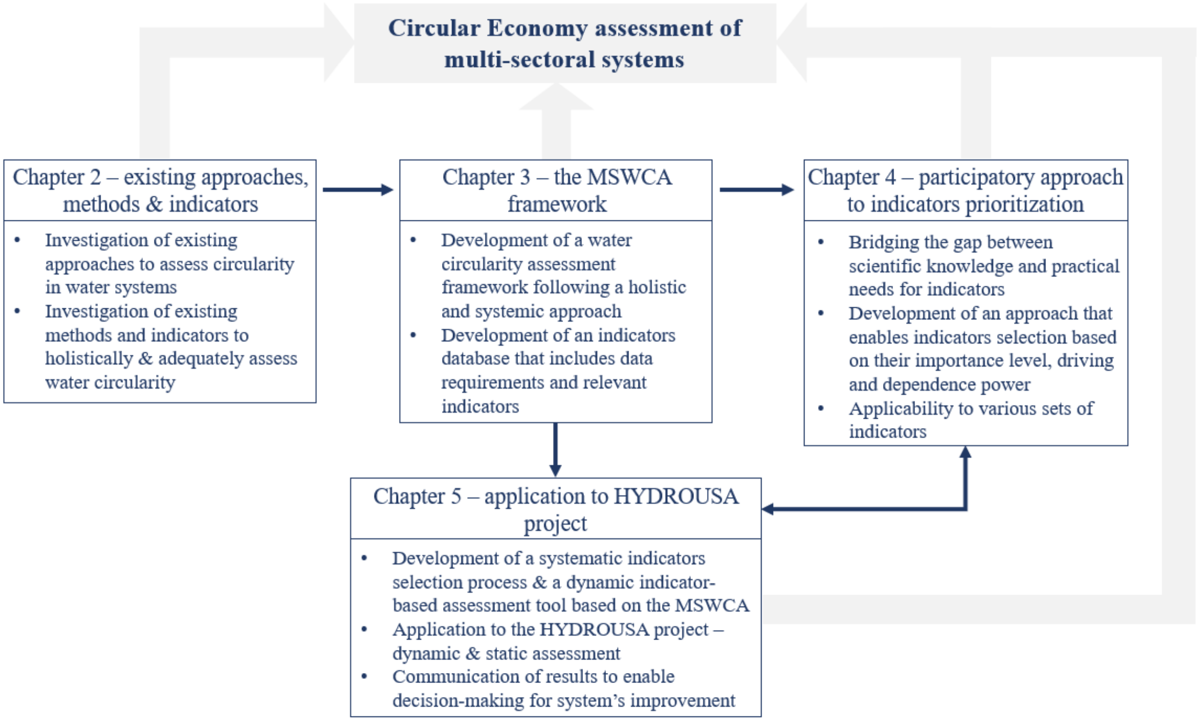


Figure 1.2: The connections between the different chapters and the main objectives of each chapter

2. Literature Review

2.1 Introduction

Water plays a critical role in human well-being, socio-economic development, as well as in sustainable ecosystem services (UNEP, 2009). Water is itself the most valuable and universal resource and at the same time, water contains nutrients and water is viewed as a carrier of energy thus, water systems intersect with all sections of society, industry and the natural environment (IWA, 2016; Arup et al., 2018). Over the past years, the increased stress on limited water resources has reached a critical level, in terms of both reduced water availability and jeopardized water quality (Sgroi et al., 2018). The ecosystems could not function without sufficient water supplies of appropriate quality, making water scarcity a key stressor in many ecosystems (Voulvoulis, 2018). On top, global demand for water is expected to exceed viable resources by 40% by 2030, if we continue business as usual (Wintgens et al., 2016). Therefore, the challenge is to meet or manage the competing demand for water, to minimize the damage to the environment and to regenerate the natural ecosystems (WWAP, 2018).

Water in nature represents one big cycle maintained by natural processes (e.g. precipitation, infiltration, evapotranspiration, condensation, etc.), which is interrupted by urbanization and by man-made water systems. Therefore, water has been pushed into the linear model of "take-make-consume and dispose", which is economically unsustainable and causes a successive degradation of water quality as water travels through the system (Stuchtey, 2015). In response to the linear pattern of growth, the adoption of the circular economy (CE) model is proposed that decouples economic growth and development from the consumption of finite sources (Murray et al., 2017; Babbitt et al., 2018; Hofmann, 2019). In order to deploy and enhance circularity, a number of studies have focused on identifying priority areas of action (Hislop and Hill, 2011; EC, 2015a; EMF, 2017b; EMF and WEF, 2017; EMF, 2018; EMF and Arup, 2019). Water was identified as one of the key priority resources by Hislop and Hill (2011). The rest of the working groups mainly focus on the consumer goods sector mentioning the preservation of water, but the importance of closing the water loops is not well addressed. Single indicators assessing the circularity of products – either qualitative or quantitative – have been developed in various academic studies. The portfolio includes the Circular Economy Toolkit (CET) (Evans and Bocken, 2013); the Material Circularity Indicator (MCI) (EMF and Granta Design, 2015); the Circular Economy Indicator Prototype (CEIP) (Griffiths and Cayzer, 2016); the Longevity

Indicator (Franklin-Johnson et al., 2016); and an economic value-based circularity metric (Linder et al., 2017). These indicators focus on the technical cycles, while disregarding the biological cycles, which are of major importance in the water sector. They target at materials preservation with strategies, such as recycling, which is only one aspect of circularity and even misleading in the water sector. Water cannot be "manufactured" by recycled materials as water is a raw material itself. Thus, preservation of materials can only be applied in the drinking water treatment plants (DWTPs) and wastewater treatment plants (WWTPs) in order to recover nutrients, salts and metals that can be used in other interconnected systems, such as agriculture and industry. These strategies are good for preserving raw materials stocks but the preservation of water stocks is poorly addressed. On the other hand, Pauliuk (2018) proposed a dashboard of new and established indicators – based on material flow analysis (MFA), material flow cost accounting (MFCA) and life cycle assessment (LCA) – to assess five main characteristics, i.e. restore, regenerate, maintain utility, maintain financial value, and maintain nonfinancial value, as well as four complementary characteristics, i.e. resource efficiency, climate, energy, and sufficiency.

In the water sector, three reports have been published up to date (i.e. Stuchtey, 2015; IWA, 2016; Arup et al., 2018), conceptually describing what should be considered in order to create circular water systems. They highlight the importance of establishing different water functionalities (e.g. consumptive and non-consumptive water, water as a durable) that would enable the balance between water withdrawals and return flows; the consideration of water, materials and energy pathways in order to create synergies within and outside the water sector. The need for an integrated urban resource management is also highlighted, looking at the water cycle "from catchment to consumer and back to catchment", following a systems approach that reveals interconnections between the human-managed and nature-managed systems. At the core of circular water systems lies the realization of the three principles identified by Arup et al. (2018), i.e. "Design out waste externalities", "Keep resources in use" and "Regenerate natural capital". However, to the best of our knowledge this approach has not yet been applied into practice for developing an assessment methodology for circular water systems.

The transition to circular water systems requires the redesign of the water infrastructure, the utilization of recent developments in technology and the integration of nature-based ecosystems to the grey infrastructure (i.e. hybrid infrastructure) (O'Hogain and McCarton, 2018). Existing concepts and approaches using and enhancing nature, such as ecosystem-based adaptation

(EbA), green infrastructure (GI), ecosystem services (ESS) and nature-based solutions (NBS), have gained momentum as they tackle challenges (e.g. climate mitigation and adaptation, water management, degradation and loss of natural capital, disaster risk reduction, etc.) in a more sustainable way, compared to the conventional hard engineering. While all four concepts share the common principle of multifunctionality, NBS can be considered as an umbrella to the other concepts with a strong solution-oriented focus and biodiversity lying at its core (Pauleit et al., 2017). Up to date, several definitions have been applied to describe NBS, e.g. the definitions provided by EC, 2015b; Cohen-Shacham et al. (2016); Raymond et al. (2017); O'Hogain and McCarton (2018); Langergraber et al. (2019a). According to them, NBS should be cost-effective, resource efficient and locally adapted. NBS are systemic interventions that bring more, and more diverse, nature and natural features and processes. They address either a specific problem (i.e. societal challenge) or multiple challenges and simultaneously provide environmental, social and economic benefits, such as biodiversity, climate change mitigation and adaptation, resilience, human well-being etc. While CE seeks to reduce environmental stress of socio-economic activities, NBS have the potential to enhance environmental and ecological status and to address human demand for natural resources. NBS can restore the crucial natural processes – by changing the fluxes of water, sediment, nutrients and pollutants – that drive the water cycle and thus, return the circularity to the water systems. NBS are also capable of resources' recovery from water, like nutrients, which fits in the natural water and nutrients cycles facilitating the transition from open to closed-loops. Therefore, the synergies fostered between the two concepts bring NBS to the forefront of enabling the realization of circular water systems.

This study is conducted in order to shed light on the assessment of circular water systems and the integration of NBS as enablers to water circularity, by addressing two main questions. What are the main parameters that should be considered in circular water systems (Sub-chapter 2.2)? And what methods could be deployed in order to holistically assess the circularity of water systems? Considering that NBS can be used as means to integrate nature to human-managed systems, a thorough investigation on the current state of NBS is carried out. This is followed by a literature review on the assessment methodologies that have been applied to evaluate their performance, including indicators that have been used/developed as metrics of performance (Sub-chapter 2.3). Current regulations and policies that act as barriers or facilitators for implementing NBS are also reviewed (Sub-chapter 2.4). The third part (Sub-chapter 2.5), reviews existing tools, methods and indicators for assessing the performance of water systems and elaborates on their suitability to evaluate key circularity aspects. The last part (Sub-chapter 2.6) concludes on what methods and indicators can be used and what is still missing in order to holistically assess the circularity of water systems.

2.2 Circularity in water systems – What needs to be measured?

In view of the lack of a water circularity definition, the white papers of Stuchtey (2015), IWA (2016) and Arup et al. (2018) are considered in this study, to understand what needs to be measured for assessing circularity in water systems. The three principles of "Regenerate natural capital", "Keep resources in use" and "Design out waste externalities" should be assessed, following the water, energy and materials/nutrients pathways. The three principles indicate the requirement of a systems approach as well as the consideration of the interactions between natural and human-managed systems. Water-related human-managed systems encompass various socio-economic sectors, i.e. urban water sector, agricultural/food sector, energy sector, and industrial sector, with agriculture and industries accounting for the highest global water withdrawals (FAO, 2016). Therefore, water circularity needs to consider all water users and not being managed at a sectoral level. To this extent, water circularity can only be achieved in a multisectoral system, including both human-managed and nature-managed systems. Natural and anthropogenic water cycles should be closed and symbiotic management of resources be promoted, avoiding burden shifting both from one sector to the other, but also from the anthroposphere to the environment. To achieve and assess water circularity, the goals of the different CE principles are explained:

The goal of the "Regenerate natural capital" principle is to ensure functional environmental flows and stocks, by reducing the anthropogenic water uses, preserving and enhancing ecosystems, and ensuring minimum disruptions from human interactions and use. In order to assess this principle, selected assets of ecological integrity and of regulating, provisioning and cultural ecosystem services are proposed to be considered. Ecological integrity targets at reducing water and nutrient loss, and storage capacity of nutrients and water (i.e. soil nutrient retention, soil organic matter, soil water storage). Regulating ecosystem services are targeted at climate regulation (i.e. sources and sinks of GHGs), groundwater recharge and nutrient regulation. Provisioning ecosystem services target at crops, livestock and fodder, while cultural ecosystem services focus on recreation and aesthetic values.

The goal of “Keep resources in use” principle is actually to close the water and water-related materials and energy loops within the system. It can be achieved by optimizing resource yields, optimizing energy and resource extraction, and by maximizing recycling and reuse. Recirculation of resources to close the loops requires sufficient quantity of the reused resources and suitable quality to meet the internal demands, which would result in a reduction of the amount of resources that are abstracted from the nature and the amount of returning flows.

The “Design out waste externalities” principle focuses on both the reduction of waste and the economic efficiency of the system, i.e. the costs of reducing waste by one unit is equal to the economic and environmental benefits of having one less unit of waste. The reduction is achieved by taking actions to achieve the “keep resources in use” principle, while the remaining waste (i.e. gaseous, liquid and solid) has impacts on the environmental system, affecting the “regeneration of natural capital” principle. Therefore, the environmental impacts, the avoided negative environmental impacts and the economic benefits and costs need to be considered in the assessment.

All three CE principles can be achieved by modifying current systems and grey infrastructure. While classical grey infrastructure can be designed to enhance water reuse and resources recovery, it differs significantly from the concept and paradigm of NBS. NBS are using natural processes, i.e. they work with nature, while grey systems (infrastructure) use additional energy to achieve circularity. Introducing NBS to urban water management naturally enhances circularity of the urban water system, hence shifts the urban water management into CE. Water in the CE should be placed without unnecessary additional energy use, which for the modification of the existing grey water infrastructure would be inevitable. In particular, the implementation of NBS can lead not only to modifications, but rather to new (hybrid) systems, more sufficiently applying the three principles. For example, constructed wetlands treating road runoff will prevent pollution of water bodies, recharge groundwater and increase biodiversity. Wetland roofs will collect and treat rainwater to be used for non-potable domestic purposes, while simultaneously acting as a natural “air conditioning” that is cost-effective and resource efficient. Therefore, NBS by exploiting their multifunctionality can facilitate the transition to circular water systems. The implementation of a single NBS may simultaneously obtain multiple co-benefits related to circularity and achieve the same result with traditional grey infrastructure, where multiple mono-functional engineering solutions are required. Additionally, the fact that NBS interconnect nature-managed to human-managed systems leads to their consideration as a key element to identifying methods to holistically assess circularity of water systems.

Any water circularity assessment can be undertaken at three different scales, i.e. micro (single components), meso (interconnected components forming a system) and macro (catchment, city, region, or national). Assessment methodologies at any scale need to take into consideration the other scales of assessment as well, in order to add significant value and become applicable. Therefore, the interlinkages that the analyzed system has with other systems and scales need to be considered as well, by providing the information required for the assessment at higher scales. Figure 2.1, which illustrates how the information obtained from the assessment at a small scale provides feedback to the next assessment scale until the puzzle of water circularity of a basin is completed.

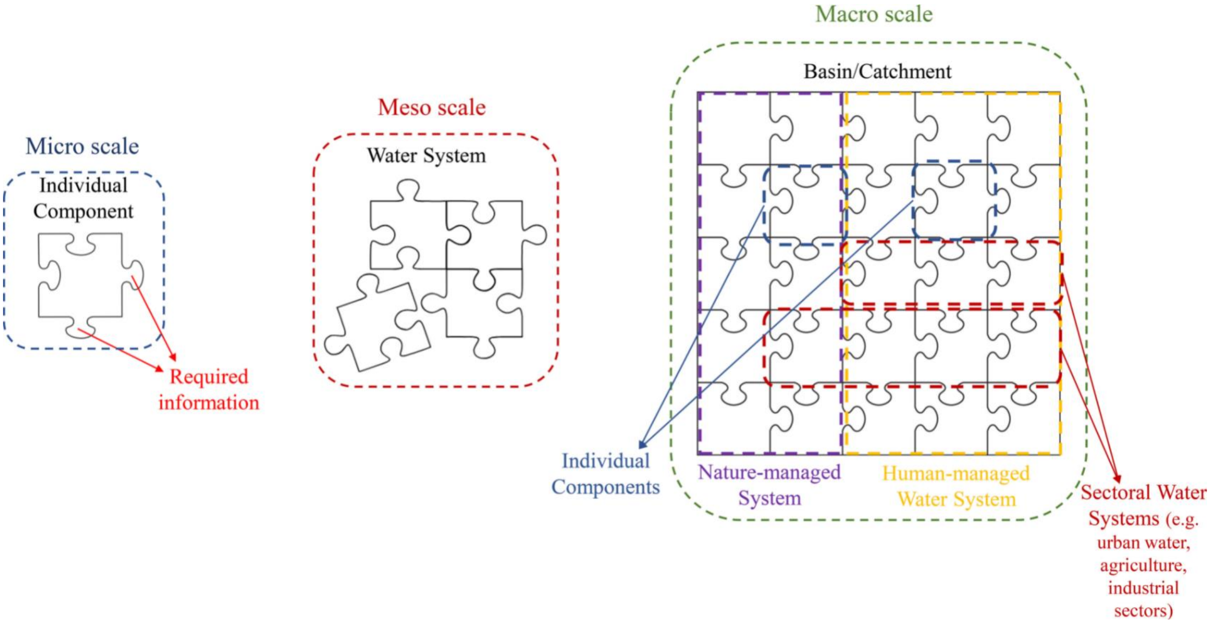


Figure 2.1: Puzzle diagram of different assessment scales

The puzzle diagram is followed in the present review of the currently available methodologies assessing NBS (at different scales) and water systems, in order to identify the “required information” that would shed light on how to assess water circularity.

2.3 NBS enabling circularity in water systems – literature review

A literature review was conducted to identify the current state of NBS to enhance circularity of water systems, targeting at publications from scientific journals identified from the databases of Scopus and Science Direct. The key words that were selected – i.e. “nature-based solution”, “water”, “water system”, “circular economy”, “circularity”, and “assessment” – were used in multiple combinations (as presented in Figure 2.2) and the search (conducted throughout the whole text) was expanded to all article types. Among the identified papers, 323 studies were categorized based on the main societal challenge to be tackled and their numerical proportions are illustrated in the pie diagram of Figure 2.2.

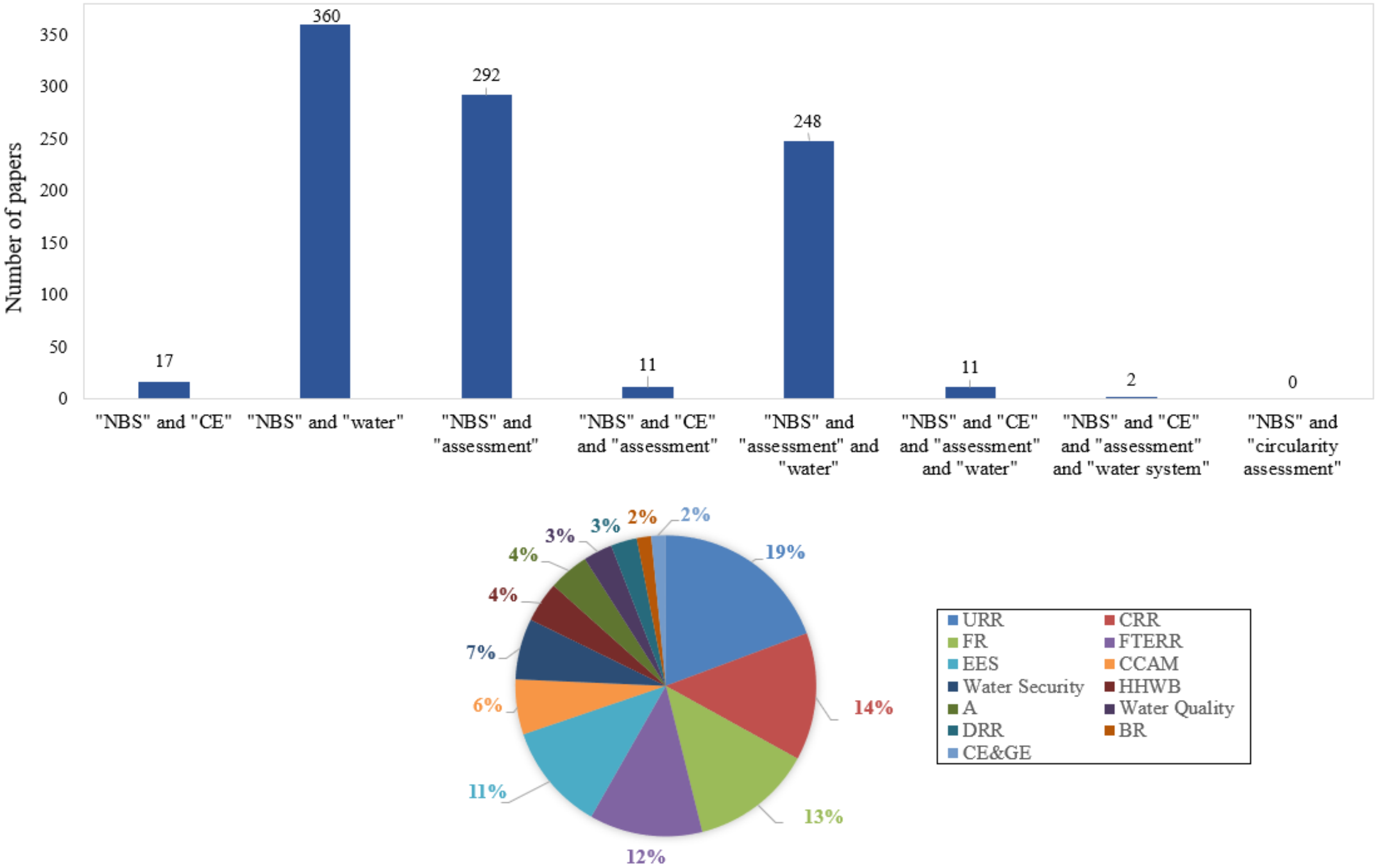


Figure 2.2: The focus of the research in the area of CE, NBS, assessment and water; and distribution of the main societal challenges among the reviewed studies (pie diagram). Acronyms: URR – Urban Regeneration and Resilience, CRR – Coastal Resilience and Restoration, FR – Flood Risk, FTERR – Freshwater and Terrestrial Ecosystem restoration and Resilience, EES – Enhancement of Ecosystem Services, CCAM – Climate Change Adaptation and Mitigation, HHWB – Human Health and Well-being, A – Agriculture, DRR – Disaster Risk Reduction, BR – Bioremediation, CE&GE – Circular and Green Economy

The connection of NBS to the concept of circularity, especially in water systems, is not well addressed by the researchers (bar chart results). Additionally, the pie diagram of Figure 2.2

illustrates that only 7% and 3% of the research focuses on water security and water quality, respectively.

The studies dealing with water security and water quality were analyzed to understand the extent to which they address water-related issues. The water-related studies assessing different aspects of NBS performance are summarized based on their context in Table 2.1.

Table 2.1: Categorization of the identified water-related studies based on their context

	Water Security	Water Quality/*Water Quality+	Water Quality & Flood Risk/*+	Water Quality & Reuse/*+	Water Quantity & Quality	Water Supply Regulation
Social aspects		Castonguay et al., 2018				
Economic aspects			Reynaud et al., 2017		Reddy et al., 2015	Vogl et al., 2017
Scenario analysis	Boelee et al., 2017		Zhang et al., 2019			
Environmental sustainability		Garfí et al., 2017				
Effectiveness		*Hernández-Crespo et al., 2017; Geronimo et al., 2019; Haddis et al., 2020; *Krzeminski et al., 2019	*Liquete et al., 2016; Jurczak et al., 2018; *Masseroni et al., 2018	*Licciardello et al., 2018		
Optimization		Andrés-Doménech et al., 2018; Cáceres et al., 2018	Moezzibadi et al., 2019			
Groundwater accounting					Bricker et al., 2017	

*+ indicates the papers that use multiple criteria in their analysis

The study of Castonguay et al. (2018) is the only one identified dealing with social aspects. This study focuses on the evaluation of different strategies for technology adoption to help decision-making by simulating the interactions of regulatory bodies and households within an agent-based model, integrating economic and environmental factors. Their results indicate that using economic instruments alone may have been insufficient to promote the adoption of rainwater tanks, and that water restrictions have had a major impact on the uptake. Additionally, the study of Reynaud et al. (2017) used a contingent valuation approach to estimate the willingness to pay (WTP) of households to different multipurpose infrastructures (conventional or green) for managing flood and water pollution. They concluded that there is an excessive willingness to pay for green infrastructure in comparison to conventional systems. The WTP in this study was influenced by people's income and their visits to Gorla Maggiore Water Park.

The optimization of certain parameters of stormwater and wastewater treatment systems (including NBS) to improve their design has been performed in three studies. Andres-Domenech et al. (2018) considered runoff characterization and volume and rainfall depth to improve the design of source control systems. Caceres et al. (2018) developed a statistical tool to select the most adequate withdrawal depth for optimizing the wastewater treatment processes. Moezzibadi et al. (2019) evaluated the filtering performance – related to suspended solids loads – of constructed wetlands to improve their design.

The technical evaluation of the NBS has been performed in the studies of Hernandes-Crespo et al. (2017), Geronimo et al. (2019), Haddis et al., 2020, Krzeminski et al. (2019), Jurczak et al. (2018), Masseroni et al. (2018), and Licciardello et al. (2018). These studies consider water quality parameters and/or water retention capacity as the main aspects of their evaluation, including in some cases costs (Licciardello et al., 2018; Masseroni et al., 2018; Krzeminski et al., 2019) and biodiversity (Hernandez-Crespo et al., 2017, Hernandes-Crespo et al., 2017). However, the scope of these studies is narrow – focusing on the technical performance or the design optimization – and they do not assess holistically the proposed solutions (e.g. potential co-benefits are excluded from the evaluation).

The studies of Chow et al. (2014), Liquete et al. (2016), Boelee et al. (2017), Bricker et al. (2017), Garfí et al. (2017), Li et al. (2017a), Radinja et al. (2019) and Zhang et al. (2019) were identified as more relevant for the purpose of this work. They either deploy a more holistic assessment or consider aspects relevant to assess water circularity (sub-section 2.3.1). The studies considering economic aspects of NBS are analyzed in sub-section 2.3.2.

2.3.1 Methodologies and indicators assessing NBS for water circularity

The eight studies identified in the previous section are categorized based on the methods that they deploy for assessment – i.e. water balance, LCA, modeling and combination of different tools. The indicators developed/used in the reviewed studies are presented in Table 2.2 and they are compared to the different water management aspects identified in EKLIPSE framework (Table 2.2) developed by Raymond et al. (2017). The sufficiency of the different aspects considered in the studies to holistically assess NBS for water management and their potential contribution to circularity of water systems are investigated.

Table 2.2: List of indicators used in the reviewed studies and their comparison to the water management criteria identified in the EKLIPSE framework

		Water management criteria identified in EKLIPSE framework															
Study	**Applied indicators**	*Runoff reduction*	*Flood peak reduction*	*Reduction of load from runoff into sewerage systems*	*Reduction of risk of flooding from flush-floods*	*Reduction of costs related to loads into sewerage systems*	*Reduction of risk of flooding from rivers*	*Infiltration increase*	*Water storage increase*	*Water retention capacity enhancement*	*Risk reduction of damages from drought*	*Evapotranspiration increase*	*Risk reduction from urban heat island effect*	*Human health & well-being improvement*	*Water quality improv. and pollutants reduction*	*Biodiversity increase*	*Carbon storage capacity increase*
Bricker et al., 2017	-							✓	✓								
Garfi et al., 2017	Metal depletion																
	Climate change																
	Terrestrial acidification																
	Marine eutrophication																
	Fossil depletion																
	Ozone depletion																
	Freshwater eutrophication																
Boelee et al., 2017	Mean species abundance						✓		✓						✓	✓	
Zhang et al., 2019	Flow reduction		✓														
	Load reductions of TSS, TP and TN														✓		
Liquete et al., 2016	Peak flow reduction		✓														
	Reduction of flooding downstream						✓										
	No. of visitors/users													✓			
	Frequency of visits													✓			
	Load reduction of dissolved organic carbon														✓		
	Load reduction of nitrogen														✓		
	Biodiversity															✓	
	Landscape diversity (Shannon's index)															✓	

	Value of wood production																
	Total construction costs																
	Total maintenance costs																
Chow et al., 2014	Increased water reuse							✓	✓								
	Reduced floodplain						✓										
	Reduced runoff volume	✓															
	Improved water quality														✓		
	Reduced energy use																
	Reduced carbon emission													✓			
	Improved air quality													✓			
	Creation of new habitats															✓	
	Capital expenditure																
	Operational expenditure																
	Land-take costs																
	Reduced water bills																
	Increased house price																
	Reduced treatment cost																
	Electricity savings																
	Natural gas savings																
	Avoided cost of CO_2																
	Avoided cost of pollutants					✓											
	Amenity value													✓			
Li et al., 2017a	Runoff volume reduction	✓															
	Peak discharge reduction									✓							
	Flood peak retardation time		✓														
	Pollution reduction (SS, COD, TN, TP)														✓		
	Civil construction costs																
	Maintenance charge																
	Utilization of rainwater resource								✓								
	Landscape value													✓			
	Ecological function												✓			✓	
Radinja et al., 2019	Reduction of combined sewer overflow (CSO)			✓													

CAPEX								
OPEX								
Amenity							✓	
Biodiversity								✓
Feasibility								

✓: directly addressed; ✓: indirectly addressed

A water balance method is used in the study of Bricker et al. (2017) that presents a vision exercise to study the impacts of different interventions on groundwater balance at city level. Water balance can be used to assess the increase in infiltration and water storage, which is one of the main considerations when assessing NBS for water management according to EKLIPSE framework (Table 2.2). However, this study does not apply a holistic assessment methodology as only one aspect (i.e. groundwater storage) is evaluated. The study of Bricker et al. (2017) is the only one identified – among the studies analysed in this section – that deploys a semi-quantitative water balance approach to investigate how specific interventions impact water systems, considering both anthropogenic and natural water flows. The consideration of mass balances from a circularity perspective (i.e. to close the water loops) are of major importance and similar studies are reviewed in sub-chapter 2.5.

LCA is used by Garfí et al. (2017) to assess the environmental impacts of a conventional infrastructure and two NBS technologies as alternatives for wastewater treatment in small communities. The indicators used for the assessment are presented in Table 2.2. One of the strongest advantages of LCA is the fact that it is a standardized and well-established method for the evaluation of the environmental impacts for the entire life cycle of a product, process, or service (ISO, 1997; Hertwich, 2005) and it is widely used to compare the environmental sustainability of different water technologies (e.g. Pan et al., 2011; Manso et al., 2018; Guertin et al., 2019; Pan et al., 2019; Oquendo-Di Cosola et al., 2020). However, when it comes to the assessment of NBS following the EKLIPSE framework (Table 2.2), none of the highlighted considerations can be addressed using LCA. There are three main constraints. Firstly, the high level of abstraction associated with the LCA results leads to potential rather than actual impacts, thus there is a generalization of the LCA impacts that do not refer to specific cases (Pizzol et al., 2015; Bai et al., 2018). NBS on the other hand should be “locally adapted”, mandating environmental evaluations to be tailored to local environments. Secondly, LCA focuses more on the environmental costs (e.g. biodiversity loss) rather than the environmental gains (e.g. carbon sequestration) (Rugani et al., 2019). Thirdly, the consideration of feedback loops between processes across the anthropogenic and the natural environment are generally neglected in LCA (Weidema et al., 2018). This means that the effects on ecosystems driven by changes occurred in the anthropogenic systems are not considered, which further neglects the consideration of the effects of those changes back to the anthropogenic systems, underestimating the actual load of the life cycle impacts. Therefore, LCA is very useful for comparing alternative solutions but not for assessing actual environmental impacts and the interconnections between natural and human-managed systems.

Modelling projected scenarios are deployed in the studies of Boelee et al. (2017) and Zhang et al. (2019) to assess the performance of NBS under future climatic conditions. Boelee et al. (2017) developed a model to evaluate the performance of alternative scenarios to address simultaneously water management challenges (i.e. water shortages, pollution, deterioration of aquatic ecosystems) and biodiversity loss, under future projections in terms of urbanization, climate change and increasing demands for food production and hydropower. Zhang et al. (2019) used a model to examine the implications of climate change on future rainfall and evaluate the reliability of Water Sensitive Urban Design (WSUD) stormwater infrastructure in pollution reduction, flow frequency mitigation and reliability as an alternative water supply. Both studies are able to address some of the key points identified in the EKLIPSE framework (Table 2.2), under dynamic time- and spatial variations of the system. However, scenario analysis modelling is more relevant for investigating options for the future rather than the actual state of the system. Therefore, process understanding modelling is considered more appropriate for water circularity assessment and relevant studies are reviewed in sub-chapter 2.5.

More holistic approaches – resulted from combination of different tools and methods – were adopted in the studies of Liquete et al. (2016), Chow et al. (2014), Li et al. (2017a) and Radinja et al. (2019). Liquete et al. (2016) deployed a runoff model, water quality measurements, biological samplings, surveys, satellite images, ArcGIS and Fragstat software to assess multiple environmental, economic and social benefits of a set of CWs surrounded by a park to treat the excess flow of mixed sewage and rainwater during heavy rain events. Chow et al. (2014) developed a systemic multi-criteria decision support framework to evaluate the design of grey/green drainage infrastructure based on quantitative measures (i.e. indicators) covering energy, environment, water quantity and quality criteria, and monetary costs and benefits. Li et al. (2017a) developed a benefit evaluation system for low-impact development of urban stormwater management measures, based on Analytic Hierarchy Process and urban stormwater model, including environmental (i.e. water quantity and quality), economic (i.e. civil construction and maintenance costs), and social (i.e. rainwater reuse, landscape value, and ecological function) benefits. Radinja et al. (2019) used a framework based on hydrology-hydraulic modeling and Multi-criteria Analysis (MCA) to evaluate co-benefits (i.e. combined sewer overflow reduction, CAPEX, OPEX, amenity, biodiversity, and ownership) of

Sustainable Drainage Systems (SuDS), resulting in favourable scenarios for stormwater control measures. Although these studies consider several water management criteria for their evaluations (see Table 2.2), water quantity – which is important to investigate the extent of closing the water loops and the enhancement of the natural water cycle – is not well addressed.

Although there is a variety of developed/used indicators among the different studies, they are not able to cover all the different aspects of water management, i.e. the water management criteria identified in the EKLIPSE framework as shown in Table 2.2. Most of the studies focus on the main societal challenge to be addressed by NBS (i.e. water quality issues and flood risk), underestimating the enhancement of the natural environment (e.g. the natural water cycle is not considered) and many co-benefits (e.g. carbon storage capacity is not evaluated by any of the reviewed studies). The fact that NBS adaptation and the resulted co-benefits are case-specific may be the reason for the evident difficulty in measuring and reporting their effectiveness. Another issue is the timescales of the monitored and experienced co-benefits (Price, 2021), as well as the spatial scale of assessment. NBS are assessed as individual components (i.e. detached from the complete water system), neglecting the whole supply chain (i.e. upstream and downstream processes and flows), the systems thinking, the interconnections between these processes and feedbacks and therefore, the impacts to the natural and urban water system. A fragmented approach of understanding isolated parts of the water system increases the risk of implementing solutions that may be inefficient due to overlooking many dynamic and aggregated effects that emerge at larger scales (i.e. due to the complex interactions of the different components with their surroundings) (Thorslund et al., 2017). The afore-mentioned observations may result in overestimation of the effectiveness of NBS (if assessed at small scales), in a lack of evidence base for the effectiveness of NBS, but also in insufficiency to assess circularity of water systems.

2.3.2 Methodologies and indicators economically assessing NBS

While NBS appear to be capable of addressing water management challenges and enhancing ecosystem services, the debate on how to valuate nature, its attributes and services in monetary terms is still open, as they are not goods directly traded in the markets (Bockarjova and Botzen, 2017). This section focuses on commonly used methods for economic evaluation of NBS – i.e. Life Cycle Cost Analysis (LCCA), Cost-Benefit Analysis (CBA), Cost Effectiveness Analysis (CEA) and Natural Capital Accounting.

LCCA is an economic assessment that accounts for all the relevant costs throughout the entire life cycle of a product, service or process, enabling the comparison between different alternatives (Bhoye et al., 2016). Life Cycle Costing (LCC) considers investment, implementation, operation, maintenance and end-of life (e.g. disposal and residual value) costs, benefits cash flows. According to the Directive/24/EU (2014) it can also include costs related to environmental externalities (e.g. greenhouse gas emissions). The results of LCCA are expressed using an economic measure, e.g. net present value (NPV), benefit cost ratio (BCR), payback period (PP) and (annual) LCC. Economic assessment based on LCCA has been performed by many researchers to evaluate the economic impacts, e.g. of rainwater harvesting systems (e.g. Roebuck et al., 2011; Amos et al., 2018a), green roofs (e.g. Ziogou et al., 2018 – including the monetization of the avoided environmental deterioration), waste management alternatives (Lee et al., 2020), urban vegetation (Sicard et al., 2018). One of the main limitations of LCCA is that environmental and economic benefits that are not easy to be monetized (e.g. reduction in urban flooding, biodiversity increase, increased property value due to aesthetic improvement, etc.) tend to get lost, potentially prejudicing the decisions (Amos et al., 2018b; Ziogou et al., 2018).

The same limitation stands for CBA, as it calculates the total costs related to a project, monetizes the obtained (environmental and social) benefits and compares the results to identify the most efficient alternative (Hansson, 2007). However, CBA is considered as one of "the most widely applied tools for economic analysis" (Balanay and Halog, 2019) and it is used to economically evaluate NBS. For example, Feng and Hewage (2018) used CBA to assess the payback period of green roofs in different markets, considering life cycle costs, public and individual benefits. CBA considering public and private costs and benefits was also deployed by Reddy et al. (2015) to assess water shortages risk of alternative scenarios (including NBS).

CEA is proposed by Boerema et al. (2018) as an alternative economic evaluation method for environmental management, in order to overcome the limitation of CBA of expressing benefits into explicit monetary terms. Therefore, CEA identifies the most cost-effective strategy by comparing the investment costs to achieve a specific goal (or measure of effectiveness, expressed in any unit), e.g. biodiversity conservation (Helm and Hepburn, 2012), greenhouse gas emission reduction (MacLeod et al., 2010), water provision improvement (Yang, 2011). However, in CEA each measure of effectiveness is treated separately (due to the different units), thus their integration for assessing whether the total benefits exceed the total costs is not always possible.

Natural Capital Accounting is defined by Philips (2017) as “a series of interconnected physical and monetary accounts that provide a structured set of information related to the stocks of natural capital and flows of services supplied by them”. Monetary accounts are referred to annual monetization of selected services, resulting in an “overall valuation of the natural asset’s ability to generate future flows of services”. For example, Vogl et al. (2017) discussed the importance of watersheds’ natural capital valuation increase (i.e. the cost of maintaining the natural capital in healthy watersheds that contributes to public good and private values) of the uptake and impact of investments in watershed services. Although non-market goods – such as many ecosystem services – do not have direct exchange values (i.e. the supply value equals the use value), Natural Capital Accounting is based on the concept of exchange value. Thus, the monetary valuation of non-market goods is based on estimations as “if a market existed” (Philips, 2017). Therefore, such estimated exchange values increase the uncertainty of this method.

Table 2.3 presents indicators that have been used in literature. While some established economic values (e.g. NPV, BCR, PP, CAPEX, OPEX) exist and are used in the studies, most indicators are case-specific. Even within the LCCA method, the LCC indicator is interpreted differently among the studies, e.g. Lee et al. (2020) consider the revenue from products, while Ziogou et al. (2018) consider the environmental cost of emissions. Especially for CBA and CAE, the costs and benefits/effectiveness measures strongly depend on the scope of each study and often the economic assessment is based on economic analysis (e.g. economic and environmental or ecologic balance) of the system rather than development of indicators.

Table 2.3: Economic indicators used in the reviewed studies

Indicator	Description	Study	Methodology	Categorization of monetized values		
				Direct economic	Environmental externalities	Natural capital
Net present value [NPV]	The sum of the annual net cash flows (i.e. the difference between cash outflow and inflow reduced by an appropriate discount rate) over the project's life time	Amos et al., 2018a	LCCA	✓		
Benefit-cost ratio [BCR]	The sum of discounted costs divided by the sum of discounted benefits (e.g. water savings) as they occur over the project's life time			✓		
Payback period [PP]	The time required to recover an investment or loan			✓		
Life Cycle Cost [LCC]	Changes in economic welfare due to the avoided environmental deterioration, i.e. consideration of construction and operational costs and environmental costs of the emissions	Ziogou et al., 2018		✓	✓	
Life Cycle Cost [LCC]	Use of the present value method, including infrastructure, operation and maintenance, collection and transportation costs, tipping fee, and revenues from beneficial products (i.e., electricity, heat, and digestate or compost)	Lee et al., 2020		✓		
Annual life cycle cost per amount of air pollutant's removal	Includes installation, planting, operation and maintenance costs, normalized per kg of O_3 removal	Sicard et al., 2018		✓	✓	
Capital expenditure [CAPEX]	Money spent to acquire, upgrade, and maintain physical assets	Radinja et al., 2019	–	✓		
Operating expenses [OPEX]	Ongoing costs for running a product, business, or system			✓		
Gross value added [GVA]	The value of goods minus the value of intermediate consumption required for the production; expressed as money per amount (e.g. euro/tonne)	Chen et al., 2019	Input/ Output	✓		
Environmental flows	Monetary estimates in 2012 US$, present value (PV)	Reddy et al., 2015	CBA			✓
Farm operations savings				✓		
Soil conservation						✓

Avoided costs from reduced pesticide use and nutrient runoff				✓		
Lower utility costs				✓		
Decreased operating costs for treatment plants				✓		
Lower water treatment costs				✓		
Direct payments				✓		
Cost	The cost per hectare of implementing a measure, per year			✓		
Cost-effectiveness	The cost of reducing GHG emissions	MacLeod et al., 2010	CEA/ marginal abatement cost curve (MACC)	✓		
Abatement potential (AP)	The total amount of GHG emissions that are reduced per year				✓	
Abatement rate (AR)	The rate at which a measure can reduce the GHG emissions per hectare				✓	

2.4 NBS for water implementation barriers and potential risks

In recent years, the concepts of circular economy and NBS have been promoted and encouraged at EU level (EC, 2015a; EC, 2015b). However, in some cases current policies and regulations, designed for a linear economy paradigm, are likely to hinder, rather than encourage, their implementation. As evidenced in the study of Stewart et al. (2016), regulations can act as barriers that prevent the adoption of innovative sustainable approaches, e.g. giving unclear messages, being complex and rapidly changing, and lacking space of manoeuvre for innovation.

The European Commission put forward a proposal for a regulation setting EU standards for reclaimed water in May 2018. This proposal is based on a JRC report (Alcalde-Sanz and Gawlik, 2017) and is related to the 2015 circular economy Action Plan (EC, 2015a), the seventh environment action programme (Decision No. 1386/2013/EU, 2013), and, globally, to the UN's sustainable development goals. The aim is to reduce water stress by promoting the use of treated wastewater in agriculture and encourage the free circulation of products irrigated with reclaimed water (Alcalde-Sanz and Gawlik, 2017) proposing a regulation that sets minimum quality standards. At present, only few EU member states have set requirements for wastewater reuse. The proposed requirements include microbiological (E. coli, Legionella spp. and intestinal nematodes) and physico-chemical parameters (biochemical oxygen demand (BOD), suspended solids (SS) and turbidity), while micropollutants are not mentioned. The proposed legislation would consider irrigation as the only application, therefore disregarding possible utilizations in NBS. Quality standards would be set according to the fit-for purpose approach. Following the World Health Organization guidelines, a risk management plan based on the multiple-barrier approach and the hazard analysis and critical control points system, analogue to the Water Safety Plan, would also be established (Alcalde-Sanz and Gawlik, 2017). However, this proposal considers solely reclaimed wastewater, that is, water complying with the quality standards detailed in the Urban Waste Water Treatment Directive (UWWTD) (Council Directive 91/271/EEC, 1991) excluding other possible sources (e.g. harvested rainwater, greywater, etc). It should be noted that the forthcoming EU standards, focused only on reuse of treated wastewater, propose improved end-of-pipe solutions that represent only a mitigation, and not a solution, of the water stress problem. Advanced concepts that would tackle reuse at decentralized level and facilitate resource recovery by source separation and source control rather than treatment need to come into force. The UWWTD states that in case the investments to build a WWTP would not produce environmental benefit or would entail excessive costs, “individual systems or other appropriate systems (IAS) which achieve the same level of environmental protection shall be used”. This creates a sort of a free zone and, as a result of this vagueness in legislation, a recent report highlights that IAS represent a significant source of pollution in EU, making the refit of the UWWTD an impellent need (EC, 2019b). In this case, the concept of IAS could be an opportunity, at EU level, for the implementation of NBS in the form of small scale, decentralized, water treatment, proven that the systems comply with the required quality standards. An example of NBS that could be a suitable option for small-scale treatment is treatment wetlands. Although treatment wetlands cover larger surfaces compared with other technologies, they do not need external energy inputs to be operated if the location allows the avoidance of pumps (Dotro et al., 2017; Langergraber et al., 2019b). This results in energy savings and lower operation and maintenance costs, which may be proven crucial in areas with limited financial resources (Langergraber et al., 2019b).

When reviewing scientific literature on NBS, little or no relevant data on the risk posed by micropollutants were found. Micropollutants have been targeted at the Priority Substances Directive (Directive/39/EU, 2013), which encompasses the Watch list system, introduced with a Commission Implementing Decision in a 2015 (EC, 2015c), then updated through Decision 2018/480 (EC, 2018a). The Watch list is a list of micropollutants that may pose a significant risk to or via the aquatic environment but for which data are still insufficient to support their prioritization and must therefore be monitored Europe-wide by Member States (EC, 2018a). Since the monitoring is to be carried out in freshwater only, there is a missing link between the occurrence of such pollutants in wastewater and the risk associated to their presence when reclaimed wastewater is reused. On the one hand, this legislative gap will delay the adoption of a common regulatory framework in the EU for water reuse/greywater/harvested rainwater or hinder its potential; in particular, this could prevent from implementing new technologies, practices and solutions – above all NBS. On the other hand, the lack of regulations on micropollutants might bring to underestimate the risk posed by such compounds.

Decentralized systems could provide an answer to this problem as they enable better source control and consequently bigger potential and safer resource recovery and reuse. Moreover, the adoption of certain NBS may even improve the removal of micropollutants compared to conventional WWTPs, as in the case of the treatment wetlands. In treatment wetlands the removal efficiencies of many compounds are reported higher than 90% thanks to the coexistence of anaerobic, anoxic and aerobic zones within surface flow, as well as the concurrence of different mechanisms, such as biodegradation, sorption, plant uptake and, in certain cases, photodegradation (Langergraber et al., 2019b; Li et al., 2014; Verlicchi and Zambello, 2014). In parallel to setting environmental quality standards, the legislation could also focus on preventing micropollutants from entering the water systems, for instance improving source control measures.

The situation outside the EU is different. In Switzerland, the Water Protection Ordinance established that WWTPs following certain criteria should be upgraded with advanced treatment by 2035 in order to ensure the removal of at least 80% of micropollutants loads, tracking WWTPs efficiency by means of periodical monitoring campaigns (Swiss Confederation, 2016). Other countries outside Europe, such as California (State of California, 2013), Australia (Australian Government, 2018) and Singapore (PUB, 2018) have implemented cutting edge policies on water reuse, including specific regulations on greywater and direct or non-direct potable reuse. In some cases, micropollutants are also monitored. The legislation of these countries might pave the way for implementation at EU level.

2.5 Methodologies and indicators assessing water systems

A lack of a holistic assessment methodology evaluating NBS as part of water systems and adequately addressing issues of water quantity, as well as the regeneration of natural capital was identified in sub-chapter 2.3. Therefore, in this sub-chapter, the research is expanded on currently available methodologies that have been applied to assess the effects of complete water systems on the physical and environmental performance in order to investigate their potential of measuring water circularity.

This sub-chapter is organized in three sub-sections according to the type of approaches deployed in the reviewed studies – i.e. studies assessing water systems and environmental compartments using MFA-based approaches (sub-section 2.5.1), Consumption-based approaches (sub-section 2.5.2), and Modelling approaches (sub-section 2.5.3). The links between these methods, NBS and circularity of water systems are identified.

2.5.1 MFA-based approaches

MFA is one of the most widely used methods to evaluate circularity (Elia et al., 2017; Pauliuk, 2018; Moraga et al., 2019). It enables a systemic quantification of materials flows and stocks, helping towards the management of resource use and the development of closed-loop systems.

Based on the principle of mass conservation in a well-defined system, MFA focuses on loadings (instead of concentrations) and provides an overview of the total system – enabling the integration of NBS to the complete water system – by linking and examining the relationship between the human-managed system and the natural environment (Hendriks et al., 2000). Focusing on water systems, many MFA-based assessment methodologies have been developed to evaluate the metabolic and sustainability performance of a specific area or system, including the development of indicators used for the assessment (Table 2.4).

In 2011, Kenway and his colleagues developed the concept of Urban Water Metabolism (UWM) that provides a systematic mass balance framework to quantify all anthropogenic and natural water flows into and out of the urban environment, resulting to quantitative performance indicators. Since then, UWM has been expanded to include energy and nutrient flows (Farooqui et al., 2016; Renouf et al., 2017; Renouf et al., 2018). Therefore, UWM can be used to assess the transition from linear to more circular metabolism of complete water systems (including the integration of NBS) that create a self-regulating sustainable relationship with the biosphere.

Similarly, Verger et al. (2018) used Territorial Metabolism (TM) to analyse the metabolism of a peri-urban area through its nitrogen, phosphorus, carbon and water flows. The main contribution of this study is the inclusion of the occurring natural processes of nutrients as part of the analysis. From a circularity perspective, the integration of nutrients in the nature-managed system is important as it is one of the aspects indicating the achievement of regeneration of natural capital principle.

Agudelo-Vera et al. (2012) developed a methodology (i.e. Urban Harvest Approach – UHA) – based on the concept of urban metabolism – evaluating and quantifying the multiple potentials of different primary and secondary (already used) resources that can be utilized within a water system (from building to city scale) in order to become self-sufficient. In 2015, Leusbrock and his colleagues expand the application of UHA to consider energy flows. UHA is close to the concept of circularity as the three deployed strategies (i.e. minimizing demand, minimizing outputs, and multi-sourcing) are similar to the circularity concepts of reduce, reuse, recycle.

Wielemaker et al. (2018) - based on the UHA – developed the Harvest to Harvest Approach (H2HA) to assess the match between the supply by new sanitation systems and the demand from urban agriculture for nitrogen, phosphorus and organic matter, in terms of quantity and quality, to foster a circular metabolism and to optimize interconnecting systems.

Table 2.4: Developed indicators in the MFA-based studies

Study	Indicator	Description/Equation	Components						
			Anthropogenic system				Natural system		
			Water	*Nutrients*	*Energy*	*Emissions*	*Water*	*Nutrients*	*Other ES*
Kenway et al., 2011	Intensity of water use	[Total water use]/[Area]	✓						
	Overall balance of inputs and outputs	[Total inputs]/[Total outputs]	✓				✓		
	Supply centralization	[Centralized supply]/[Total water use]	✓						
	Rainfall harvesting	[Decentralized sources]/[Rainfall]	✓				✓		
	Centralized supply replaceability	[Rainwater or wastewater or stormwater]/[Centralised water supply]	✓						
	Total use replaceability	[Rainwater or wastewater or stormwater]/[Total water use]	✓						
	Replaceability of total use with wastewater and stormwater	[Wastewater + Stormwater flows]/[Total water use]	✓						
	Anthropogenic turnover rate	[Anthropogenic system inputs]/[Stored water]	✓				✓		
	Rainfall turnover rate	[Natural system inputs]/[Stored water]					✓		
	Total turnover rate	[Total inputs]/[Stored water]	✓				✓		
Farooqui et al., 2016	Internal harvesting ratio	[Internally harvested freshwater volume]/[Total water volume supplied to meet demand]	✓						
	Internal recycling ratio	[Internally water recycled volume]/[Total water volume supplied to meet demand]	✓						
	Water extracted	[Extracted water volume from external sources]/[Population of the urban area]	✓				✓		
	Energy used	[Total water-related energy use]/[Population of the urban area]			✓				
	Stormwater runoff ratio	[Post-development stormwater runoff]/[Pre-development stormwater runoff]	✓				✓		
	Total stream discharge ratio	[Post-development discharge]/[Pre-development discharge]	✓				✓		
	Infiltration ratio	[Post-development groundwater infiltration]/[Pre-development groundwater infiltration]					✓		
	Evapotranspiration ratio	[Post-development evapotranspiration]/[Pre-development evapotranspiration]					✓		

Renouf et al., 2017	Urban water efficiency per person	Total use of ‘environmental’ water per person	✓				✓		
	Urban water efficiency per unit of functionality	Total use of ‘environmental’ water per unit of urban function	✓				✓		
	Water-related energy efficiency per person	Total energy use for the water system per person			✓				
	Water-related energy efficiency per unit of functionality	Total energy use for the water system per unit of functionality			✓				
	Nutrient recovery from urban water	Proportion of the nutrient load in wastewater that is beneficially utilized		✓					
	Water supply internalization	Proportion of total water demand met by internally harvested/recycled water	✓						
	Water use within safe operating space	Rate of surface and groundwater drawn from supplying catchments relative to the sustainable urban water allocation					✓		
	Water pollutant load within safe operating space	Point-source and diffuse nutrient loads discharged to surface and groundwater relative to sustainable discharge rates						✓	
	Hydrological performance	Post-urbanized hydrological flows/fluxes relative to pre-urbanized flows/fluxes	✓				✓		
	Supporting diverse functions	Water needed to maintain desired functions relative to water allocated for the functions	✓				✓		
Verger et al., 2018	Efficiency for nitrogen, phosphorus and carbon flows	[Local consumption]/[Total production] **and** [Local consumption]/[Total consumption]		✓				✓	
	Self-sufficiency capacity for nitrogen, phosphorus and carbon flows	[Production]/[Consumption]		✓				✓	
Agudelo-Vera et al., 2012	Demand minimization index (DMI)	[Baseline demand – Minimized demand]/[Baseline demand]	✓						
	Waste output index (WOI)	– [Exported waste]/[Minimized demand]	✓						
	Self-sustainable index (SSI)	[Harvested resources – Exported resources]/[Minimized demand]	✓						
	Resource export index (REI)	[Exported resources]/[Minimized demand]	✓						
Leusbrock et al., 2015	Energy recovery index (ERI)	– [Recovered and reused energy]/[Minimized demand]			✓				
	Self-sufficiency index (SSI) for thermal, electric and total energy	[Thermal/electric/total energy produced]/[Minimized thermal/electric/total energy demand]			✓				
	Resource export index (RXI)	[Exported energy]/[Minimized demand]			✓				
Wielemaker et al., 2018	Self-sufficiency index (SSI) for nutrients	[Resource reused]/[Minimized demand]		✓					

Numerous indicators are resulted from MFA-based studies that are able to quantitative and qualitatively measure the metabolic performance and self-sufficiency of water systems. The developed water-, nutrient- and energy-related indicators cover both anthropogenic and natural flows, but extended natural nutrient flows are disregarded (i.e. the consideration of natural nutrient cycles). This way, the extent of closing the water-loops and the regeneration of natural capital in terms of water is achievable. However, emissions and natural nutrient processes and flows and other ecosystem services are disregarded in these indicators.

MFA-based assessment approaches can form the basis for a water circularity assessment methodology of water systems as they have the capability of including both the human-managed and the nature-managed system (i.e. particularly useful when NBS are part of the analysed system), and simultaneously consider flows, stocks and loadings of the water, materials and energy pathways. However, other approaches need to be incorporated in order to consider additional environmental impacts, additional environmental benefits and ecosystem services, as well as economic aspects in order to fully assess the ability of regenerating the natural capital and designing out waste externalities.

2.5.2 Consumption-based approaches

Consumption-based approaches quantify the resources (including water) required to produce goods and services "consumed" by society and estimate the associated embodied lifecycle environmental impacts, whether those impacts occur inside or outside the defined boundary of the system (Baynes and Wiedmann, 2012). LCA is one of the most representative methods of this category and one of the most widely-applied to assess the environmental impacts of water systems (see Section 3), as well as to assess systems from a CE perspective (Elia et al., 2017; Pauliuk, 2018; Baleta et al., 2019; Moraga et al., 2019). The indicators used in LCA are well-known and they are not presented in this study.

Different practices or technologies to recover raw materials (e.g. phosphorus) and energy, as well as to reuse water from wastewaters have been investigated, by assessing or evaluating technical (e.g. Zhou et al., 2017), environmental (e.g. Pintilie et al., 2016; Amann et al., 2018; Dominguez et al., 2018; Hao et al., 2019; Pradel and Aissani, 2019; Sylwan et al., 2019) and economic (e.g. Laitinen et al., 2017) aspects. Additionally, Buonocore et al. (2018) used LCA to compare the environmental impacts of linear, partially circular and circular scenarios of energy recovery and water reuse in WWTP. Leong et al. (2019) compared the environmental

(LCA) and economic (LCC) impacts of centralized and decentralized options for non-potable water uses at a domestic and commercial building. Similarly, Zanni et al. (2019) compared the environmental impacts and other technical aspects (e.g. system's complexity, tanks, pumping system etc.) of centralized and decentralized water systems at single dwelling and apartment buildings. Assessment of environmental impacts of the entire urban water system was investigated in the studies of Lemos et al. (2013) (considering environmental impacts), of Lane et al. (2015) (comparing conventional to diversified urban water infrastructure) and of Xue et al. (2019) (considering both environmental and monetary costs). However, the above-mentioned studies – trying to address circularity issues by focusing mainly on the environmental impacts – fall short of keeping water as the protagonist in terms of circularity (i.e. there is no proof of closing the water loops). Thus, they are not able to make an overall evaluation of the CE benefits (i.e. elimination of waste and regeneration of natural capital). It is also reported that the application of LCA in complex multifunctional circular water value chains with multiple outputs (i.e. water, energy, materials) and water uses is still challenging (Reap et al., 2008; Bobba et al., 2018). Therefore, although these studies have assessed aspects of circularity (i.e. environmental impacts, economic efficiency, etc.) of different components of water systems, they cannot holistically assess the circularity of water systems.

However, LCA if combined with other tools/methods can provide useful information in terms of environmental sustainability as part of a water circularity assessment. For example, the CE principle of design out waste externalities, can be assessed with LCA especially if combined with LCC or other economic assessments to incorporate the economic aspects of the system. Additionally, LCA has been integrated to metabolic approaches (in Goldstein et al., 2013; García-Guaita et al., 2018; Sohn et al., 2018) in order to assess the sustainability of cities' metabolisms, considering the anthropogenic flows of different materials. However, to the best of our knowledge, such methodological integration has not been performed to water-related metabolisms.

2.5.3 Modelling approaches

MFA-based and Consumption-based approaches can be used to evaluate the circular metabolism (i.e. in terms of water in both human- and nature-managed systems, of energy and of nutrients mainly in human-managed systems) in a stationary (snap-shot) mode and the potential environmental impacts of the entire life cycle to the environment, respectively. However, the actual environmental impacts, the environmental benefits and in general the degradation or regeneration of the natural environment (e.g. considering the nutrients natural cycles) is not well-addressed. Therefore, modelling approaches are reviewed in this sub-section in order to bridge this gap by studying different material cycles simultaneously, in addition to interpreting them individually, while gaining insight into the magnitude of the associated flows. The purpose is to present the state-of-the-art of existing models (as tools that can potentially be incorporated in assessment methodologies) and existing methodologies (deploying modelling approaches) that can be used towards a holistic water circularity assessment.

Process-based and conceptual hydrologic and biogeochemical models have been developed to simulate the water and nutrients (or solutes) transport, fate and cycling. Such models are based on a theoretical understanding of relevant ecological processes (i.e. using partial differential equations, kinetic laws, stoichiometry and balance equations) (Cuddington et al., 2013) that enables the consideration of multiple and complex interactions between climate, soil, geology, vegetation, hydrology and nutrient balances. In addition to this feature, computer models interpret dynamically the analyzed system due to the inclusion of temporal and spatial variation and resolution – in comparison to the stationary nature of the MFA- and Consumption-based approaches. However, the main drawback of such models is the required amount of data (field and experimental data and model results), which increases with increasing mechanization of the model, as well as the complexity of the model. Data-intensive complex models impede their wide implementation and use, thus more generic models are required that are simpler and easier to apply (Vadas et al., 2013).

The reviewed tools (i.e. models) are categorized according to their focus. Pure hydrological models focus on the quantification of the hydrological partitioning, i.e. partitioning of precipitation into streamflow, evapotranspiration and storage change. Agro-hydrological models simulate hydrology, agricultural water management and in some cases nutrient loads of agricultural areas. Hydro-biochemical models simulate the transport fate and cycling of nutrients on soils and land use, including agricultural areas.

Starting with the reviewed hydrological models, Bellot and Chirino (2013) developed an eco-hydrological modelling approach (i.e. HYDROBAL) for assessing the water balance with a daily resolution. More precisely, HYDROBAL investigates the temporal variability in soil-water content determined by vegetation water uptake as a function of climatic conditions (i.e. daily rainfall and micrometeorological variables) and the model outputs include actual evapotranspiration, runoff, and aquifer recharge (deep percolation). Zhang et al. (2020)

developed a conceptual catchment water balance model based on the proportionality hypothesis (denoted PWBM) to model the hydrological partitioning across spatial and temporal scales. The PWBM model inputs require precipitation, potential evapotranspiration and leaf area index and the model outputs are streamflow, evapotranspiration and storage change. Westenbroek et al. (2010) developed a modified Thornthwaite-Mather Soil-Water-Balance (SWB) code – combining geographic information system (GIS) data layers and tabular climatological data – to calculate spatial and temporal variations in groundwater recharge. Li et al. (2017b) developed a model – integrating conceptual models in the vadose zone (considering various landscape units, e.g. farmland, grassland, surface water, bare soil, etc.) and the groundwater flow model FEFLOW under GIS – to simulate the hydrological processes under various scenarios of water-saving activities. The model was applied in the Heihe River Basin in Gansu Province of China and validated by comparing the simulated evapotranspiration, groundwater levels and the total water balance with remote sensing results, previous studies and monitored data.

One of the most extensively used agro-hydrological model at the field scale is the FAO-56 dual crop coefficient (FAO, 2016; Allen et al., 1998) model that estimates the crop water requirements by means of the simulated evapotranspiration and its two components, i.e. evaporation and transpiration. Another agro-hydrological model that can be used to investigate irrigation, nutrient and salt management strategies is the research version of the SWB model (i.e. SWB-Sci) that is a mechanistic, real-time, generic crop growth, soil water, nutrient and salt balance model (Annandale et al., 1999; Annandale et al., 2000; van der Laan et al., 2010; van der Laan et al., 2014), consisting of different submodules (e.g. water balance sub-module and the nitrogen submodule). The Soil and Water Assessment Tool (SWAT) simulates water quality and quantity, the impact of land use, management practices and climate change (Arnold et al., 1998; Arnold et al., 2012). Automatic irrigation algorithms in SWAT have been tested, improved and validated to correctly simulate the hydrological processes in agricultural catchments in response to climate change and water management scenarios (e.g. Dechmi et al., 2012; Githui et al., 2016; Wei et al., 2018; Uniyal and Dietrich, 2019).

Hydro-biogeochemical models simulate the transport, fate and cycling of nutrients on agricultural areas and soils, considering the interactions with the hydrological processes. DRAINMOD-P (Deal et al., 1986; Tian et al., 2012; Askar, 2019), HYPE (Lindstrom et al., 2010), INCA-P (Wade et al., 2002; Jackson-Blake et al., 2016), RZWQM2-P (Ma et al., 2012; Sadhukhan and Qi, 2018) and Simply-P (Jackson-Blake et al., 2017) are some of the existing models focusing on the phosphorus transport in soils, summarized in the review of Pferdmenges et al. (2020). The models presented here are the ones that are capable of simulating both surface (diffusion, desorption and erosion) and subsurface (infiltration and transport in soil) phosphorus processes, as well as phosphorus plant uptake. Additionally, all the presented models include all the hydrological compartments (i.e. surface water, infiltration, groundwater and streamflow), which are important if water cycle is included in the analysis. Their differences mainly lie on the different water flow and solute transport approaches that they use (e.g. storage routing representation or empirical or Darcy or Richards equations, and single/dual porosity and dual permeability etc.) and on the spatial scales (i.e. soil profile, plot/field and catchment). Additionally, the process-based CENTURY model (Parton et al., 1987) has been extensively used to dynamically estimate the soil organic carbon stocks. The CENTURY model is designed to simulate carbon, nitrogen, phosphorus and sulfur dynamics in natural or cultivated systems, using a monthly time step (Parton et al., 1988; Shaffer et al., 2001), allowing the simulation of the anthropogenic (land management) and natural (climate and soil) drivers, with the possibility to assess the effect of alternative scenarios. Other models developed to track and estimate the carbon sequestrated or emitted from both plantations and managed native forests are the CO2Fix (Mohren and Klein-Goldewijk, 1990), GORCAM (Schlamadinger et al., 2000) and FullCAM (Richards and Evans, 2004; Waterworth et al., 2007).

The review of hydrological, agro-hydrological and hydro-biogeochemical models revealed that there is a variety of available models, capable of simulating the environmental processes of water and nutrients. Hydrological and agro-hydrological models an provide more accurate quantification of the hydrological processes on different temporal scales (daily, monthly, seasonal, annual) that can be used as inputs to water balance equations, considering both anthropogenic and natural water flows, in order to holistically assess the circularity of water systems. Biogeochemical models can shed light on the underestimated nutrients cycling in nature and carbon sequestration, that would further improve the environmental and physical assessment of the system, as well as the evaluation of the environmental benefits. Therefore, such models can effectively include NBS (as most of them use environmental processes to address societal challenges) and can be used within a water circularity assessment methodology integrating the ecosystem perspective, which is currently the missing element within the other reviewed approaches and methods. However, to the best of our knowledge, these models have not been incorporated to water assessment methodologies; thus, indicators targeting at the ecosystems cannot be identified in this case. The selection of the model to be incorporated in a water circularity assessment methodology is of major importance as models with high complexity would burden their wide use and adoption, while very simplistic models would not accurately describe the system, resulting in unrealistic conclusions. The model should also be able to sufficiently and simultaneously describe the environmental processes of water and all nutrients in order to avoid the need of incorporating different models for different purposes, which would result in high complexity and computational time. Attention should be given in case that such models are used in parallel with consumption-based approaches (such as LCA), as the actual environmental impacts resulting from the former and the potential impacts resulting from the latter may conflict with each other and be double counted.

The previously reviewed models have been used as standalone tools by the researchers. Villarroel-Walker (2010) developed a Multisectoral Systems Analysis (MSA) methodology for understanding and managing the metabolism of complex systems, supported by a set of socio-ecological indicators. The environmental model was coded in MATLAB, incorporating Substance Flow Analysis (SFA) and Regionalized Sensitivity Analysis (RSA), in order to track and account for the movement of water, energy, nitrogen, phosphorus, and carbon into, around, and out of a regional-city system, considering multiple socio-economic sectors (i.e. water, energy, food, forestry, and waste management) and the interactions amongst them. However, the focus of this study is on the production system rather than the water system itself with the developed indicators (Table 2.5) covering aspects of circularity (i.e. the direct or indirect regeneration of natural capital and the design out waste externalities from its environmental dimension). The indicators are not able to evaluate the principle of keeping resources in use by measuring the extent of closing the water, energy and nutrients loops.

Table 2.5: Developed indicators in Villarroel-Walker, 2010

			CE principles						
			Regeneration of natural capital		**Keep resources in use**			**Design out waste externalities**	
Study	**Indicator**	**Description**	Direct	Indirect	Water	Nutrients	Energy	Environmental	Economic
Villarroel-Walker et al., 2012	Productivity indicator (PRI)	Measure of useful products generated within the system per unit of resources consumed		✓					
	Resources usage indicator (RWI)	Measure of resources consumed per unit of waste requiring disposal		✓				✓	
	Eco-efficiency indicator with respect to wastes (PWI)	Measure of the amount of products per unit of disposed waste						✓	
	Eco-efficiency indicator with respect to emissions (EEI)	Measure of the amount of products per unit of emission to the environment, either to the atmosphere or to water bodies	✓					✓	
	Health of air emissions (HAE)	Measure of the ratio between the actual amount of emissions to the atmosphere and a healthy emission level	✓						
	Health of water emissions (HWE)	Measure of the ratio between the actual amount of emissions to water bodies and a healthy emission level	✓						
	Waste equals food (WEF)	Compares the amount of products versus the quantity that the system would generate if no flows are classified as waste and all emissions correspond to healthy emissions		✓				✓	
	Eco-effective indicator (E2I)	Encloses together the concepts of waste equals food and healthy emissions, describing thus the overall eco-effectiveness of the system						✓	

2.6 Summary of main findings

The current review addressed two main questions regarding circularity in water systems: What needs to be measured to assess water circularity? and How can water circularity be measured?

The answer to the first question was found in the white papers of Stuchtey (2015), IWA (2016) and Arup et al. (2018), and it is the realization of the three CE principles of natural capital regeneration, keeping resources in use and designing out waste externalities. The water, nutrients and other materials, as well as the energy pathways need to be followed within both human- and nature-managed systems (Arup et al., 2018). This analysis would enable the consideration of physical (natural and anthropogenic water, nutrients, materials and energy flows), environmental (actual impacts, e.g. increase or loss of biodiversity, and potential impacts, e.g. global warming potential) and economic (e.g. eco-efficiency) aspects. Most of these aspects can be measured using already developed indicators (Table 2.6).

Regarding the second question, a variety of existing methodologies and tools were identified that have been presently used to assess NBS for water management, water systems, and water-related environmental compartments. These methodologies are capable to measure the different aspects of water circularity, as illustrated in Table 2.6.

Table 2.6: Methodologies, tools and indicative indicators measuring different aspects of circularity; *Abbreviations: W: water, QN: quantity, QL: quality, N: nutrients, BDV: biodiversity, DMR: demand minimization of resources, E: energy, WR: waste reduction, En. I: environmental impacts, Ec. I: economic impacts*

	Evaluation of:													
	Regeneration of natural capital					Keep resources in use			Design out waste externalities			Integrated system	Additional aspects
	W cycle		N cycle	BDV	DMR	W	N	E	WR	En. I	Ec. I		
	QN	QL											
Tools													
Hydrology- hydraulic models	✓												✓
Water quality measurements		✓											✓
Biological samplings				✓									
Surveys													✓
Satellite images													
ArcGIS													✓
Fragstat													
Hydrological models	✓									✓			
Agro-hydrological models	✓	✓	✓							✓			
Hydro-biogeochemical models	✓	✓	✓							✓			
Methods													
UWM	✓	✓				✓	✓	✓				✓	
TM						✓	✓						
UHA					✓	✓		✓	✓				
H2HA					✓		✓		✓				
LCA										✓			
MSA			✓		✓				✓	✓		✓	
LCC											✓		

Indicative indicators
e.g. Hydrological performance (Renouf et al., 2017)
e.g. Water pollutant load within safe operating space (Renouf et al., 2017)
-
e.g. Mean species abundance (Boelee et al., 2017)
e.g. DMI (Agudelo Vera et al., 2012)
e.g. Internal harvesting & recycling ratio (Farooqui et al., 2016)
e.g. SSI (Wielemaker et al., 2018)
e.g. ERI (Leusbrock et al., 2015)
e.g. WEF (Villarroel-Walker et al., 2012)
Actual: e.g. HWE (Villarroel-Walker et al., 2012) **Potential**: e.g. Global warming potential (GWP) (from LCA)
e.g. Avoided cost of pollutants (Chow et al., 2014)
e.g. PRI (Villarroel-Walker et al., 2012)
e.g. Landscape value (Li et al., 2017a)

The information given in Table 2.6 can be used to get better insights on what is still missing to holistically assess the circularity of water systems. The lack of a holistic water circularity assessment methodology is apparent, as well as a water circularity assessment framework to rigidly frame the assessment methodologies. However, there is a variety of existing methods and tools that if incorporated are able to cover all the different aspects of circularity assessment in water systems. Additionally, although a wide set of indicators exists in the literature covering most of the aspects of circularity, indicators measuring the environmental performance of water systems in terms of natural nutrients cycles are still missing. The existence of numerous indicators does not necessarily mean that they are capable of adequately and holistically measure circularity in water systems. The development of a water circularity assessment methodology would prove their adequateness and a potential requirement for the use of new indicators.

3. Water Cycle and Circular Economy: Developing a Circularity Assessment Framework for Complex Water Systems

3.1 Introduction

Water in the environment follows a natural circular model that secures water resources by regulating water flow and ensuring water quality. However, in human-managed systems that follow a linear model of economic growth, water is successively qualitatively degraded after use, becoming unfit for further use both by humans and ecosystems (Stuchtey, 2015). To decouple economic growth and development from imprudent resource consumption, the alternative model of Circular Economy (CE) is been promoted aiming to achieve resource efficiency, to reduce waste production and to improve environmental, economic and social sustainability (European Commission, 2015a). To stimulate CE uptake, water, phosphorous and metals have been identified by Hislop and Hill (2011) as key priority resources.

Beyond its necessary preservation, water is a carrier of energy and materials. The most obvious connection between water and CE is seen in the transition of wastewater treatment plants to resource recovery facilities, motivating the recovery and valorisation of treated wastewater, materials (e.g. nutrients, organic matter, etc.) and energy efficiency (Zhijun and Nailing, 2007; Sgroi et al., 2018; Voulvoulis, 2018). Other non-conventional approaches that could enhance resources circularity are the use of alternative water sources (e.g. rainwater and stormwater harvesting, etc.), the decentralized sanitation and reuse model and the ecological sanitation model (Abu-Ghunmi et al., 2016). However, fragmented management and implementation of such models is unlikely to result to desired outcomes from a CE perspective. A more holistic water circularity approach is proposed by five corporate bodies (i.e. McKinsey & Company, International Water Association, Arup, Antea Group and Ellen MacArthur Foundation) in three white papers (i.e. Stuchtey, 2015; IWA, 2016; Arup et al., 2018). The authors have identified the need for an integrated water management approach from local to river basin, encompassing different sectors (i.e. systems approach), differentiating between water functionalities (i.e. resource, consumable, durable) to enable reuse and recycling, symbiotically managing resources (i.e. water, materials and energy) and considering the multiple interactions between "nature-managed" and "human-managed systems". Three CE principles were developed and adapted to sustainable water management – i.e. Regenerate Natural Capital, Keep Resources in Use, and Designing out Waste Externalities – in an effort to create a common basis for the development of a CE framework for water (Arup et al., 2018). The "Regenerate Natural Capital" principle aims to ensure functional environmental flows and stocks, the "Keep Resources in Use" principle focuses on closing the resource loops, and the "Design Out Waste Externalities" principle targets at the economically efficient reduction of waste (Nika et al., 2020a).

However, such an integrated approach would require to overcome existing barriers. Integrated water management requires application of integrated models enabling systematic analyses to investigate interconnections, synergies and antagonisms between the different sectors and resources (Villarroel-Walker and Beck, 2012), as well as the feedback loops between the technosphere and the biosphere. Integrated management and modelling further indicate the need for data sharing, availability and security (Ludwig et al., 2014). Moreover, successful implementation of CE in water requires innovations promoted through a social and institutional context, as well as the establishment of appropriate regulations and standards (Heshmati, 2015). Although in many cases innovative technologies are already available (e.g. resource recovery from wastewater), hindered CE implementation is attributed to the lack of planning and design methodology capable to identify the most appropriate solutions, tailored to individual cases (van der Hoek et al., 2016). Difficulties have been also identified in valuing environmental benefits against economic costs, as well as the relationship between environmental practices and corporate competitiveness and profits in an effort to find the right incentives for companies to implement CE (Sartal et al., 2020). The latter becomes more challenging for water valuation as current water pricing policies do not account for external costs (i.e. externalities) related to economic, social and environmental aspects (Greyson, 2007; Hislop and Hill, 2011).

In this study, a comprehensive analysis of water within the concept of CE is being conducted in an effort to address current challenges through the development of a game changing circularity assessment framework. The proposed Multi-Sectoral Water Circularity Assessment (MSWCA) framework follows a multi-sectoral approach, focusing on both economic and non-economic (i.e. ecosystems) sectors and symbiotically managing multiple resources. It reveals the complex interconnections and interdependencies between the different sectors. In this work, the term sector is used to group the resource-oriented activities of an area that support the economy and have a direct or indirect impact to water resources. The MSWCA applies integration of models and approaches for circularity assessment in line with the three CE principles, covering physical, technical, environmental and economic aspects. An indicator database has been developed as part of the framework, allowing data circulation and enabling comparability of different systems. A qualitative showcase of the MSWCA framework in a fictional case study is also presented in this work, allowing a better understanding of its implementation and use.

3.2 Water circularity

3.2.1 Water in the centre of CE

Naturally, the hydrological cycle is influenced by weather, climate and physical characteristics of the area (i.e. land and soil formations, vegetation and geology), meaning that land use/land cover (LULC) and climate changes significantly impact the hydrological cycle (Ma et al., 2008). A disrupted hydrological cycle directly affects ecosystems, species and therefore biodiversity, which in turn is critical to water and nutrients cycling (Lange et al., 2019). Hydrological cycle alterations are further induced by water withdrawals resulted from the various socio-economic activities; e.g. agriculture accounts for 69% of the global water withdrawals, industries for 19% and municipalities for 12% (FAO, 2016). Additionally, water with degraded quality that is returned to the basin (i.e. qualitative withdrawals) may result in substantial chemical and biological consequences to human health, ecosystems and biodiversity (Davis et al., 2016), but also to amenity and economic activity. Figure 3.1 illustrates the interdependencies between the different socio-economic and non-economic (i.e. natural environment) sectors.

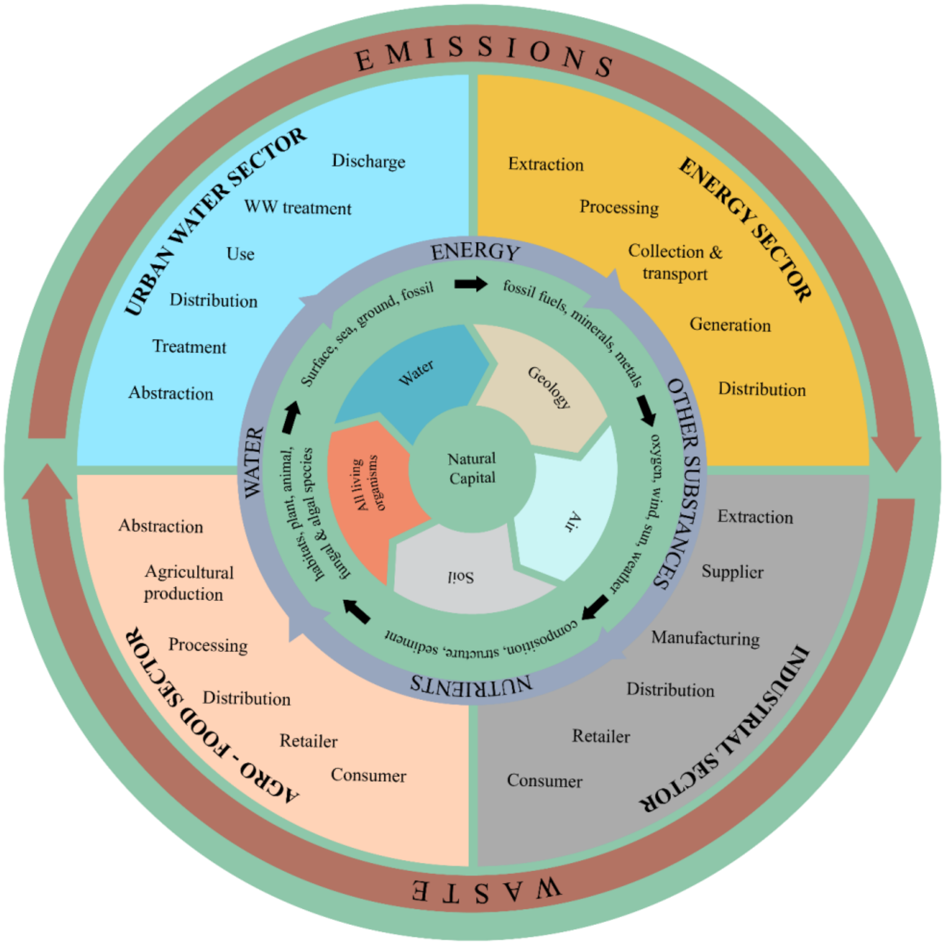


Figure 3.1: Multi-sectoral process diagram illustrating the interdependencies between the different sectors and the natural environment in terms of water and other resources

The feedback loops – occurring in the naturally interconnected system – show that any change has an inevitable effect to all the different components of the system (i.e. the ripple effect) (Everard, 2004). Thus, water is the ultimate systems challenge. Although this ripple effect is increasingly acknowledged in various cases, water management is still fragmented (Everard et al., 2016). Socio-economic sectors are artificially divided with water being managed at sectoral level (and seldom at river basin level) and considered as an isolated component of the ecosystem. An example of the ripple effect caused by sectoral management can be seen in China’s policy to address food security by achieving self-sufficiency of 95% that resulted in irreversible depletion of water resources and in increased stresses to ecosystems and biodiversity (Ghose, 2014).

The transition to a holistic and integrated water management at river basin scale was the rational of the European Water Framework Directive 2000/60/EC (WFD), which in spite its initial recognition as a ground-breaking environmental directive, failed to achieve the initial targets. The failure is attributed to the lack of efforts towards the implementation of the systemic approach mandated by the Directive (Voulvoulis et al., 2017). The systemic approach appears as a prerequisite for CE (EMF, 2013), raising concerns of amplified risks and not reaching the expected results to water resources, ecosystems and biodiversity in case that efforts are concentrated in sectoral rather than integrated management.

In this context, the development of a holistic circularity assessment framework is required that would enable and support a strategic circular water management approach. The MSWCA framework is encompassing both socio-economic (i.e. water, energy, agro-food, other related industry and waste handling) and non-economic (i.e. ecosystems) sectors, to overcome the issue of fragmented water management.

3.2.2 Circularity prerequisites

The effective implementation of circularity involves the identification of clear circularity pathways, e.g. water circularity focuses on using the right water from multiple water sources (i.e. surface and groundwater, desalinated water, industrial brine and wastewater, rainwater and stormwater, greywater and blackwater) for the right purpose to the right users in a synergetic combination of centralised and decentralised water systems. Such approach implies the application of different water functionalities (Stuchtey, 2015) that enable a targeted and effective multi-sourcing, recycling and reuse of water. However, in many cases, the circular models do not fit as the arisen challenges are not technical but rather policy related, leading to difficulties to make a step change. Therefore, the actual implementation of water functionalities requires the establishment of water quality standards and appropriate policies and regulations at both the centralized and decentralized levels, supporting the concept of water circularity.

Circularity performance assessment additionally requires the specification of clear circularity targets, presented as CE principles by Arup et al. (2018), i.e. Regeneration of Natural Capital, Keep Resources in Use, and Design out Waste Externalities. The CE principles indicate the consideration of environmental, technical, physical and economic aspects in the assessment, as well as the symbiotic management of water-related materials and energy. The World Forum on

Natural Capital defines natural capital as “the world's stocks of natural assets, which include geology, soil, air, water and all living things”. The Natural capital principle aims to ensure functional environmental flows and stocks. “Keep resources in use” CE principle targets the reduction of extraction/abstraction of natural resources and minimization of waste generation by closing the water, water-related materials and energy loops within the system. The ‘Design out Waste Externalities’ principle targets the reduction of negative externalities by turning them into positive outcomes. Externalities can be both positive (e.g. monetary value attributed to clean water, biodiversity etc.) or negative (e.g. monetary value attributed to pollution) and result from producing or consuming a good or service. Any kind of waste and/or emissions (solid, liquid, gaseous) potentially causes environmental impacts translated to negative externalities. Thus, waste reduction and reuse result in reduction of negative externalities and in potential increase of positive externalities.

The MSWCA framework enables the incorporation of the three principles to holistically assess the target system.

3.2.3 Symbiotic management of resources and dynamic interactions

Water feedback loops and the associated ripple effect require the implementation of systems approach by using multi-sectoral analysis. However, water can be seen not only as a resource but also as a carrier, both in the human-managed and nature-managed systems; e.g. nutrients are diluted in water, thus their transport, fate and natural cycling is controlled to a high extent by water, while in the human-managed systems various substances (including nutrients, minerals, metals and other) are concentrated in used water, which can be seen either as a cause of pollution or as an opportunity for resource (other than water) recovery, valorisation and reuse. Energy embodied in water can also be recovered and used.

Holistic multi-sectoral assessment implies the simultaneous investigation and management of multiple resources (i.e. water, energy, nutrients and other materials) as they flow through the different socio-economic and non-economic sectors. However, symbiotic management of resources at multi-sectoral systems increases the complexity of managing supply and demand, due to numerous supply and value chains; more complicated and dynamic interactions and incorporated processes between them; and various environmental, economic, social and regulative aspects.

To adequately describe the behaviour of the system and enable the circularity assessment, covering all different aspects, integration of methods, models and metrics is required (Nika et al., 2020a). The intrinsic purpose of circularity is to reduce the amount of resources used by increasing their recirculation and reuse (i.e. closing the resources loops), which indicates the need for quantification (Saidani et al., 2019). Therefore, Material Flow Analysis (MFA) and Substance Flow Analysis (SFA) are widely used to assess circularity (Pauliuk, 2018; Moraga et al., 2019). They systematically quantify the flows and stocks of materials in systems, differentiating between flows of goods (e.g. drinking water) and flows of substances contained within these goods (e.g. nitrogen) (Pivnenko et al., 2016). On the other hand, the effects resulted by closing the resources loops (i.e. consequential circularity) need to be investigated as well, which has led to an increased use of LCA-based methods to assess this aspect (Saidani et al., 2019). While MFA can be applied at different levels of sophistication enabling its use in complex systems, LCA generally neglects the feedback loops between the anthroposphere and the biosphere (Weidema et al., 2018) hindering its use in complex systems where interactions between socio-economic and ecological systems are of major importance. Feedback loops are observed at different time scales, resulting from "fast" (i.e. occurring over days and years) and "slow" (i.e. occurring over decades and centuries) processes (Ward et al., 2019). A "fast" process is water withdrawal or crop yield, while a "slow" process is change in biodiversity. Consequential circularity is therefore suggested to be assessed by coupling natural and human system models in an effort to investigate and predict complex system behaviour, emerging from non-linearities, time lags and unexpected results caused by feedback loops. Natural system models are referred here as numerical models to simulate the natural system's behaviour and dynamics. Nika et al. (2020a) presented a variety of hydrologic and biogeochemical models to simulate water and nutrients (or solutes) transport, fate and cycling. Other types of natural system models including ecological models, such as modelling of biodiversity change, or water quality models, etc. also exist and may be required to be coupled. On the other hand, human system models vary from analytical tools – such as MFA and LCA – and more complex agent-based models to capture human system's dynamics by incorporating market processes, human decision making and behaviour.

Integrated modelling or nexus approaches to deal with interdisciplinary issues emerging from CE and water-related concepts (e.g. Sponge City) or even from water management are increasingly acknowledged in the recent literature. For example, available tools investigating interlinkages between different sectors are suggested to be used as city circularity tools in the review paper of Paiho et al. (2020). However, the reviewed tools mainly focus on the socio-economic sectors, while natural environment is underestimated by not being an integral part of the analysis. On the other hand, Nguyen et al. (2020) incorporate ecosystem services in the developed integrated assessment framework but as the focus is on Sponge Cities, it lacks models or approaches targeted at assessing circularity in human-managed systems. Li et al. (2018) developed a watershed modelling framework to "represent the coevolution of the water-land-air-plant-human nexus in a watershed", but the investigation of circularity is again out of the scope of this study.

Working towards the direction of integrated approaches, the MSWCA framework allows the assessment of multi-sectoral systems characterized by interdependencies and feedback loops. It suggests the integration of MFA, LCA and economic models for the socio-economic sectors (i.e. human system), and hydro-biogeochemical model(s) and ecological indicators/modelling for the natural/biophysical system to investigate the natural system's dynamics and behaviour, within a single modelling framework. However, the purpose of the developed framework is not to specify the exact models (both the number and the modelling software) to be used, but rather to recommend concepts and modelling approaches that are required for a multi-sectoral systems assessment. There is not a unique combination of models and tools, as the most appropriate natural and human system models are case-specific. For example, if natural ecosystems (such as forest) form a major component of the studied system, then biogeochemical models, considering macropore flow of phosphorus, may be more appropriate compared to the studied system in which agriculture plays a major role with conventionally tilled soils where macropore flow is less pronounced (Pferdmenges et al., 2020). Additionally, the number of the models and tools to be coupled should be decided with cautious. The higher the number of coupled models and tools, the higher the complexity of the integrated model is, impeding its application.

Therefore, the MSWCA framework considers the interconnections between the different sectors in terms of water, energy, nutrients and other substances/materials flows and enables the incorporation of feedback loops – in terms of physical responses and not human behaviour – between the different socio-economic sectors and between the anthroposphere and biosphere as well. More complex agent-based modelling that investigates the human system's dynamics can be coupled to the integrated model at a later stage (if necessary).

3.2.4 Common baseline for data requirements

The effectiveness of integrated water management depends on accurate information resulted from a holistic assessment; while the effectiveness of the assessment framework depends on securing access to accurate data from different sources (Figure 3.2). Collection, standardization, homogenization and exploitation of the multiple heterogeneous and fragmented data sources that are required for a holistic multisector circularity assessment is not trivial.

Historical data are conventionally collected for different purposes from diverse disciplines following various methodologies and structure resulting in inconsistent forms, resolution and terminology. Water data are currently trapped in silos, rising issues of data accessibility, ownership, trust, interorganizational-competition, security and privacy for data-sharing among the interested parties. In many cases, there is also a lack of consensus on relevant data needed to feed the frameworks, resulting from different philosophies in data importance. Regarding environmental data related to nature-managed systems, there is a two-tier data regime. There are fields with very good protocols and metadata (e.g. weather and climate), whereas there are fields that are underdeveloped in terms of data requirements and reporting (e.g. nutrients cycling, ecosystem services, etc.). Therefore, decision-makers are often hindered to compare management options, make informed decisions balancing economic, social and environmental interests, and subsequently evaluate and prioritize potential solutions.

To overcome this bottleneck, common data policies, data management infrastructures and shared data systems are required between public and private decision-makers, stakeholders and practitioners. Therefore, an indicators database, including every data instance required for a holistic approach, is developed within the MSWCA framework.

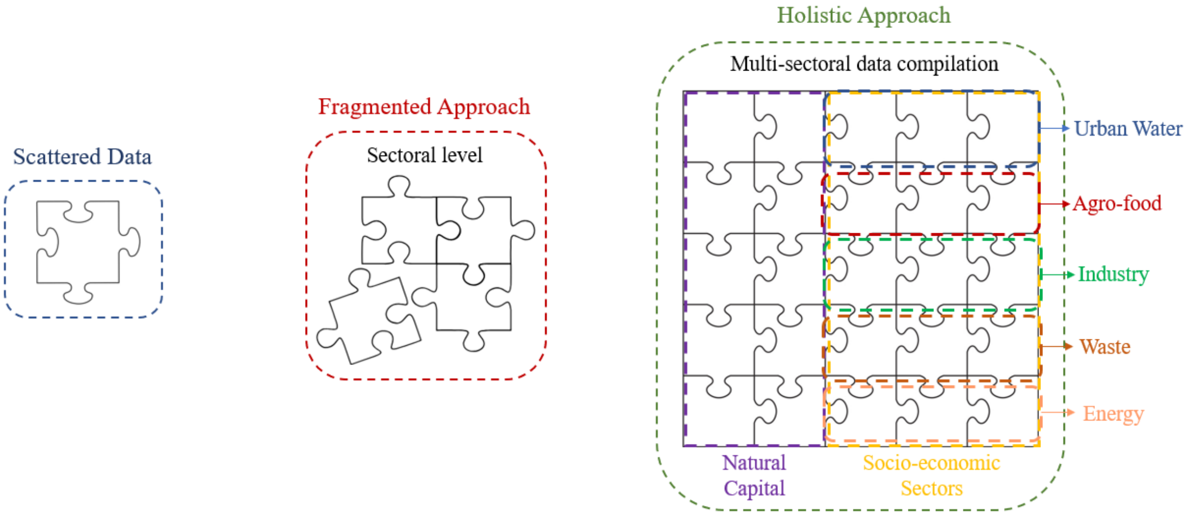


Figure 3.2: Data requirements for building the puzzle

3.2.5 Data gathering and models uncertainty

There are several levels of uncertainty associated with the modelling process, from the input data (i.e. quality, reliability, data processing protocols) to the model or sub-models structure (i.e. conceptualization inaccuracies, omission of significant mechanisms, ill-defined boundary conditions) and the linkage between different water-subsystems or between human sectors and the natural environment (i.e. gaps in knowledge on the interactions between human–natural systems and their boundaries, issues with the integration of fast and slow process dynamics between natural and human systems). The robust quantification of uncertainties and risks of the model outputs increases the predictability and practicability of the model and helps decision makers to develop an understanding of the reliability and impact of the uncertainties on the model estimations.

The complexity of an integrated circular water management assessment model increases with the increase of sectors and components (i.e. agro-food, energy, waste, natural capital). Mapping of the uncertainty sources, their magnitude and their relationships is a significant step in the analysis (Uusitalo et al., 2015). The holistic model should consider uncertainties from the different water sub-systems modelled and uncertainties due to the coupling of the sub-systems (Tscheikner-Gratl et al., 2019). However, there are differences in the perception of uncertainties across the environmental modelling and integrated water modelling community and across the different water sectors and a standardized methodological approach to identify, quantify, reduce, report and communicate uncertainties is still missing (Bach et al., 2014; Montanari, 2007; Vanrolleghem et al., 2011). An overview on uncertainty sources for the integrated water modelling can be found in the study of Tscheikner-Gratl et al. (2019), whereas a practical approach for the quantification of uncertainty in integrated water models is proposed by Tscheikner-Gratl et al. (2017). Five generic steps have been identified for handling uncertainties in Integrated Environmental Models (IEMs) incorporating ecosystem services (Baustert et al. (2018)): 1) location, 2) identification, 3) characterization, 4) treatment and 5) communication of the uncertainties in a cyclic and iterative process. Techniques commonly applied in each of these steps are also discussed.

In the current work, the following techniques are suggested to be implemented for the assessment, reduction and control of uncertainties (Li et al., 2018): i) application of a data-model fusion and data assimilation framework to integrate heterogenous data into the required spatial and temporal dynamics and constrain the used water models (Keenan et al., 2011; Li et al., 2018; Liu and Gupta, 2007), ii) application of multi-objective and multivariate calibration techniques to reduce the bias of the model (Rouholahnejad et al., 2012; Zhang et al., 2013) and iii) implementation of global sensitivity analysis in which the variation range of all input parameters is considered simultaneously; the contribution of input parameters to the total model error is assessed for the entire range space of the input parameter (Borgonovo and Plischke, 2016; Gan et al., 2014; Sarrazin et al., 2016)

It is also suggested to expand the boundaries of the uncertainty assessment beyond the calibration/validation and uncertainty assessment phases. Uncertainties can be located, identified and mapped during the model conceptualization stage considering the model goal and scope, the model structure and required parameters (considering acceptable uncertainty ranges while accounting related risks). Specific consideration is required for the efficient and standardized communication of the uncertainties to the relevant stakeholders (Baustert et al., 2018).

3.2.6 Valorisation of resources and market analysis

The Principle No. 4 of the Dublin Statement on Water and Sustainable Development (International Conference on Water and the Environment, organized by the United Nations; Dublin, Ireland, January 1992) highlights that “not recognizing the economic value of water generally leads to wasteful and environmentally damaging uses of the resource. Managing water as an economic good is an important way of achieving efficient and equitable use, and of encouraging conservation and protection of water resources". Therefore, value "of water" and "in water" is included in the MSWCA framework, revealing and assessing the economic aspects of the CE principles: Design Out Waste Externalities (e.g., optimization of water resources use through sufficient and correct valuation of water); Keep Resources in Use (e.g., optimization of resource yields obtained from water – energy, nutrients, minerals and chemicals – and water reuse); Regenerate Natural Capital (e.g., correct valuation of natural capital through non-market methods, such as pollution prevention, natural capital restoration, etc.).

3.2.6.1 Value of water

In order to adequately value water, different types of uses in market and non-market sectors must be characterized. Water as an economic good in market sectors, can be considered as an intermediate or a consumption good. Intermediate goods are employed to make final products (e.g., agriculture, industry), while consumption goods provide direct human satisfaction (e.g., water used by households). In the case of intermediate goods, the economic theory of a profit-maximizing producer provides the conceptual valuation framework, while in the case of consumption goods the theory of the utility-maximizing consumer is used (Young and Loomis, 2014; Spellman, 2015). As with any other environmental resource, economic value is measured by the aggregation of many users' revealed preference or willingness to pay (WTP). WTP is straightforward elicited in the case of market prices, since prices set by market equilibrium show the WTP by the buyer at the margin. Similarly, for non-marketed goods, the WTP elicitation constitutes the theoretical basis to calculate "shadow prices". The theoretical foundations of nonmarket economic valuation of environmental resources are well developed (Freeman, 2003). Since market valuation varies according to spatial, qualitative and temporal attributes, non-market valuation (or 'shadow pricing') of water should follow similar rules. Economists additionally consider the existence of other non-use values, such as future option, existence and bequest values, however, the focus of this study is on the economic valuation of use values as an instrument to consider in circularity assessment.

The conventional demand or marginal benefit function is the concept measured in economic valuation approaches. For sectors such as agriculture (i.e., irrigation), industry and households (or residential use), an abstract demand function can be formulated in order to connect water use (demanded quantity) and price, together with other factors influencing demand (e.g., income, temperature). Water services (e.g., provision, urban sanitation and treatment) are generally provided under monopoly (public, private or both) and prices do not generally change enough to elicit a demand function. In this case, a great amount of observations on transactions is needed in order to have sufficient variation in price. Additionally, cross-sectional data from different water service suppliers in different municipalities or locations may also offer sufficient price variation. Under this approach, parameters of demand functions can be estimated by using statistical inference and econometric techniques. An alternative valuation approach for sectors using water as intermediate good (or service), such as agriculture and industry, bases on the residual value. If appropriate prices (as determined by the market) can be assigned to all inputs but one, the remainder of total value of product is imputed to the remaining or residual input, water.

Non-market valuation approaches can be divided into either "revealed preference" or "stated preference" approaches, which are both used to elicit the value of water in different sectors (including the environment) and to economically assess environmental positive and negative externalities from economic sectors affecting water resources (e.g., ecosystem degradation, water pollution). As in the case of market valuation (based on eliciting a demand function upon observed behaviour), these methods also base on observed behaviour of water users. Revealed preference methods rely on observations of actual expenditure choices made by users (revealing their preferences) and approach market valuation by inferring the net WTP upon observed changes in user’s expenditure for different levels of the environmental resource (i.e., quantity, quality). This approach generally uses travel cost, hedonic pricing, and choice modelling methods. Under the assumption of utility maximization, users’ WTP can be inferred upon their revealed preferences. In the case of stated preference, methods base on the simulation of a hypothetical (non-existent) market in which respondents (or users) are asked to express WTP for existing or potential environmental features. The deployed methods are choice modelling – in this case when hypothetical alternatives are ordered by respondents’ preferences – and contingent valuation method (CVM). CVMs are based on a survey to a sample of respondents (water users) with the aim to elicit how much money respondents will be willing to pay or willing to accept (WTA) to maintain the existence of (or to be compensated for the loss of) an environmental resource or service. Stated preferences of the surveyed individuals are thus obtained.

The proposed MSWCA framework accounts for different methodologies to assess the value of water, since an adequate implementation of the CE principles require the use of both, market and non-market valuation methods depending on the considered sector and the service/externality to be valued. Specifically, market valuation method will be used to estimate demand curves upon available data in the different sectors and nonmarket valuation will be preferably performed based on stated-preference methods, though depending on the specific case-study, revealed-preference methods could also be adequate. It is worth noting that nonmarket valuation faces some potential weaknesses, which need to be considered. Though evidence suggests that stated preference methods are able to provide valid and reliable estimates, a carefully designed survey and sampling procedure to gather the required information are of extreme importance. Hypothetical bias, aggregation bias, moral satisfaction, and scope sensitivity represent some of the main limitations that stated preference methods need to handle (Kahneman and Knetsch, 1992; Morrison, 2000; Harrison and Rutström, 2008). In the case of revealed preference methods, though widely accepted by economists as reliable valuation methods, observed behaviours do not usually provide all information needed to deliver valid estimates in all cases (Haab and McConnel, 2002). Consequently, the use of both methods is usually recommended when sufficient data is available. Additionally, commented limitations are more likely to occur in the case of non-use values (which are not the focus of the proposed framework).

3.2.6.2 Value in water

The proposed MSWCA framework takes also into account the value in water. Recoverable materials carried by water and recovered energy depend on the water source (e.g., hydrologic system, waste water, reclaimed water), the specific market needs and regulations, and production process requirements of the system. Valorisation of these resources is straightforward based on market valuation techniques since market prices exist for all these materials/resources. Extraction and conveyance costs should be valued. The benefits of resources incorporation (e.g., energy from thermal sources, nitrogen for agricultural uses) can be assessed by Life Cycle Assessment (LCA) approaches, through evaluating the environmental positive impacts achieved by using these reclaimed resources (compared to alternative sources) in all the stages of a product's life. Additionally, using alternative "in water" resources can provide cost savings in the production process (e.g., energy savings), which can be assessed by Life Cycle Cost (LCC) economic analysis (Marín, 2015). Environmental benefits, such as reduction/elimination of negative environmental externalities related to mineral extraction (e.g., water, soil and air pollution), achieved savings in energy power from polluting sources, avoidance of excess nutrient loads in water bodies, etc., can be economically valued by non-market approaches, as described in previous section. In this sense, LCC helps to identify and assess circularity measures to be implemented in complex water systems. Although LCC economic analysis is simple to understand and perform, and helps to assess circularity and resource efficiency, it also has some limitations. On one hand, it is mainly valid on the micro level (e.g., specific production processes), where data scarcity and calculation uncertainty may represent relevant limitations. On the other hand, LCC is inadequate for assessing environmental impacts (mainly due to market and information failures), being recommended the use of LCA to complement LCC (Kambanou and Sakao, 2020). In this regard, it is worth noting that though LCA might imply higher implementation complexities in terms of inputs and resources needed, studies such as Walker et al. (2018) and Potting et al. (2017) assert that circularity indexes should be supported by LCA approaches. The circularity assessment approach proposed in this study takes into account the use of both analytical approaches, LCA and LCC, with the aim to assess the value in water.

3.2.7 Measuring and assessing circularity

Circularity assessment involves a complex multi-sectoral systems analysis managing different resources and considering feedback loops and interdependencies. Such a complicated analysis inevitably produces complicated results, which require simplification in order to facilitate communication and comparison. The use of indicators is a common practice in complex systems to simplify results visualization (Lu et al., 2019).

In the developed indicators database (Section 4), the selection of appropriate existing and newly developed indicators targets at a holistic evaluation of the three CE principles, i.e. three different sets of indicators, one indicator set per principle. The indicators are further differentiated in data-oriented indicators (i.e. indicators provided by stakeholders), information-oriented indicators (i.e. calculated indicators from modelling) for system's understanding, and action-oriented indicators (i.e. Circularity Performance Indicators calculated from modelling) for circularity assessment. Thus, information overload is avoided but at the same time access to information-oriented and data-indicators offer the possibility of understanding underlying factors, processes, or interactions that are linked with circularity.

3.3 The MSWCA framework

In this section, the conceptual Multi-Sectoral Water Circularity Assessment (MSWCA) framework is presented, aiming to bridge gaps and synthesize highlighted aspects mentioned in previous sections. The framework (Figure 3.3), includes five distinct phases namely, system development, system synthesis, system analysis, assessment and system testing. The main components of MSWCA are MFA, natural systems models and economic valuation. Information-oriented and Action-oriented (i.e. Circularity Performance Indicators, CPI) indicators, as well as sensitivity and uncertainty analyses are incorporated into a modelling framework. MSWCA follows a multi-sectoral system approach similar to the one developed by Villarroel-Walker (2010). MSWCA considers different socio-economic (i.e. urban water, energy, food/agriculture, industry, waste handling) and non-economic (i.e. natural environment) sectors and targets the symbiotic management of resources (i.e. water, energy, nutrients and other materials) as they flow through the different sectors. The modelling approach enables the investigation of the feedback loops between the socio-economic sectors and the environment, as well as of the complex interactions between them. Therefore, synergies and antagonisms among the different sectors are revealed and a balance between socio-economic activities and environmental resilience is promoted. The MSWCA is developed in line with the following principles:

- To unlock data trapped in silos and overcome data inefficiencies by developing an indicators database;
- To promote systems approach by assessing multi-sectoral systems incorporating various resources, making natural capital an integral component of systems circularity;

- To estimate both the value in and of water by considering both market and non-market sectors;
- To holistically assess the circularity performance of multi-sectoral systems – both at systems and sectoral levels – considering sensitivity and uncertainty analyses; and
- To evaluate the impact of future interventions to achieve future circularity targets.

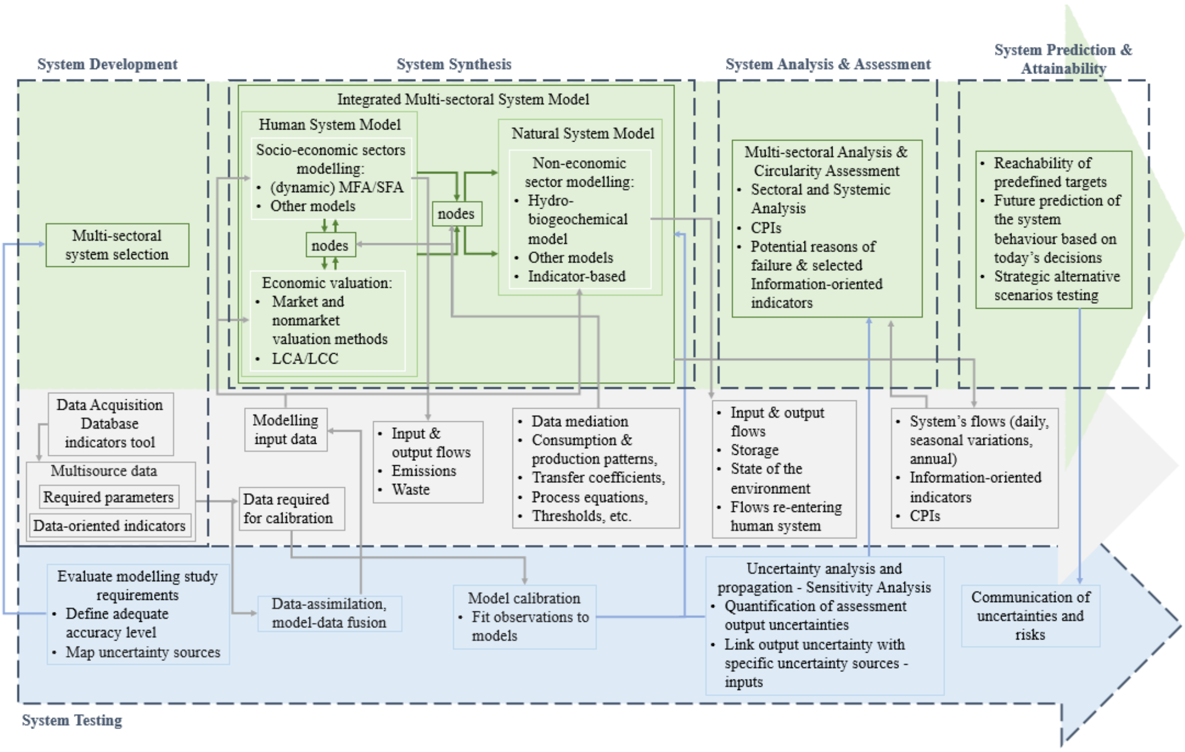


Figure 3.3: The MSWCA framework illustrating the different modelling phases and data flows (within the grey arrow in the middle)

MSWCA stages include:

System development: This phase involves the selection of the multi-sectoral system. All the involved socio-economic sectors are specified and the system boundaries are expanded to include the physical boundaries of the surrounding natural environment. The sectors include all the relevant unit processes (process diagrams of the selected socio-economic sectors - Figure 1) and consider the flows of the targeted resources (i.e. water, energy, nitrogen, carbon, phosphorus, other materials). The inclusion or not of other materials/resources, such as metals, minerals, cellulose etc. depends on the market needs and the additional industrial sector of interest in order to utilize and valorize the specific material.

The second phase of data acquisition is of major importance as it directly affects the quality, accuracy and precision of the results. Data acquisition enables the calculation of natural and anthropogenic flows of resources, therefore general data (e.g. climate, geomorphology, LULC), water, energy, nutrients/other materials uses, soil and water quality, resource recovery, etc. are required. Additionally, the state of certain ecological parameters is required to enable correlation between them and natural resource cycles. Several sources of information may be used to obtain the required data. The source of information is related to the uncertainty level of the model and therefore to the sensitivity analysis. In order to form a common baseline for data acquisition related to multi-sectoral systems an indicators database is developed, correlating the required data – obtained in terms of required parameters and data-oriented indicators – to information-oriented and action-oriented indicators for circularity assessment (Section 4).

System synthesis: The first phase of system synthesis involves the geospatial representation of the studied multi-sectoral system, i.e. land use land cover of the system, including number and type of buildings (in their actual location) and population.

The next phase – built upon the previous one – is the development of the integrated model for the multi-sectoral system that includes four modelling components, i.e. the socio-economic sectors, the non-economic sector (i.e. natural environment), their nodes of intersection, and the system as a whole. The socio-economic sectors are modelled using MFA based on developed mass balances. The resource flows (i.e. water, nutrients, energy and other materials) required to solve the mass balances are calculated based on available data, consumption and production patterns, mass transfer coefficients and process equations. The establishment of resource patterns, transfer coefficients for each process and the application of different products lifetime functions enable the establishment of dynamic MFA that would facilitate the integration to the natural system models. Computational models can be also used to estimate specific resource flows or air emissions in case that higher precision is required. The developed resource balances – for each of the socio-economic sectors - result in quantification of inputs and outputs, waste (including emissions to air, water and soil), accumulation, internal resource reuse/recycling and resource/materials to be recirculated to another socio-economic sector. At this stage, the information to be transferred from each socio-economic sector to the others, as well as to the natural environment (i.e. input to the natural system model) is specified. The different socio-economic sectors are interconnected in the model via nodes, indicating their physical interactions. The nodes can be simulated using linear, nonlinear and differential equations, thresholds, if-then rules and demand-supply functions, integrating market simulation that is based on economic valuation and analysis. The nodes also act as modules performing data mediation (both semantically and structurally interoperable data flows, according to Wang and Grant, 2019) to enable data transfer from one model to the other. The complexity of nodes simulation increases significantly if complex agent-based models (ABM) are integrated that can be used to simulate diffusion of innovation and adoption, changes in policies, individual behavior, etc.

The non-economic sector, i.e. the natural environment, is modelled using natural system models and input data resulted from the human system models (e.g. water withdrawals, irrigation water, nutrients inputs, emissions, etc.) and entering the natural system models via the feedback loop nodes. Static data (e.g. soil and management conditions, soil type and formations, hydraulic conditions, etc.), as well as dynamic data (e.g. weather conditions) obtained through data acquisition procedure are also used as model inputs. Hydro-biogeochemical modelling – enabling an integrated investigation of water, carbon, nutrient and sediment dynamics – is suggested to simultaneously simulate the water and nutrients transport, fate and cycling. Mass transfer is at the core of such models using a series of (differential) constitutive equations based on various processes (e.g. diffusion, reaction etc.) and their corresponding coefficients (e.g. diffusion or mass transfer coefficients). Forces and fluxes are computed to solve field balance equations. Additionally, ecological parameters, such as biodiversity, soil erosion, etc. are included in the model in the form of indicators. As their relationship with the water and nutrients cycles is not straightforward, statistical approaches can be used to investigate correlations. The modelling output is mainly the quantification and qualification of different resources flows that re-enter (via the feedback loops nodes) or affect the socio-economic sectors.

Integrated modelling is interacting – via the nodes – with market analysis and economic valuation. For the non-economic sector of natural environment, non-market valuation approaches, i.e. revealed preference and stated preference methods, are deployed for the economic valuation of water resource. For the socio-economic sectors, the economic valuation targets water as an intermediate good, water as a consumption good, and indirect resources recovered from water, using market valuation techniques. For the recovered resources, LCA and LCC, physical, chemical, and mechanical properties and regulatory standards are included in the analysis. Therefore, this phase focuses on the elicitation of the value of water and of recovered resources in the different sectors and on the investigation of positive and negative externalities occurred from the socio-economic sectors, affecting the natural capital.

At this stage, the multi-sectoral system's model is solved and calibrated (see the following section of System testing) for the year of data acquisition and the identified indicators are calculated.

System analysis: The results of the integrated model are interpreted. Graphical representations, flow diagrams, table matrices, etc. are created, enabling the multi-sectoral analysis of the system in terms of holistic performance, synergies, antagonisms, feedback loops and identification of hotspots. The system analysis phase is completed with the circularity assessment based on specific circularity metrics (i.e. Circularity Performance Indicators – CPIs). The CPIs consist of a set of whole-of-system and sector-specific indicators and are categorized based on the CE principle that they target, holistically assessing circularity of multi-sectoral systems incorporating various resources.

System testing: Activities to identify, characterize, treat and communicate the uncertainties of the MSWCA are dynamic and run in parallel to all MSWCA stages, from the selection of the multi-sectoral system and conceptualization of the modelling study, to the model integration and evaluation of the assessment outputs. In the initial phases of the system development, uncertainty sources are mapped (qualitatively or quantitatively) and prioritized. Acceptable levels of uncertainty are also defined in this phase. This can help evaluate the system boundaries selected, the completeness of sectors and flows considered in the assessment and guide the data collection (i.e. identify data that will impact significantly the assessment output focus effort to improve their quality) and model section processes (i.e. identify the requirements and the temporal and spatial resolution of the models). The uncertainties map can be updated during model development.

The integration of data and models used in the assessment is an important step in the analysis and needs to follow a systematic data assimilation framework, to combine the heterogenous streams of data with the models accounting for the related uncertainties in a transparent and statistically robust way. During the integrated modelling phase, special attention is required to the calibration techniques followed; the parameters of the model need to be selected to maximize the fit of the model with the data. It is suggested either to calibrate the integrated model simultaneously (can be computationally expensive) or to calibrate the upstream model (e.g. the natural system model) and gradually integrate and calibrate the downstream modules (e.g. the human system model, etc.).

To investigate how the variability of input conditions and how uncertainties of the inputs and models are translated into uncertainties of the integrated model outputs, uncertainty and global sensitivity analyses are performed. The sensitivity analysis indicates important parameters that significantly affect the reliability of the assessment results. Uncertainty analysis is used to obtain probability distributions, the integrated model outputs and indicators based on the probability distributions of the input data. The uncertainty of the model's output due to the uncertainty in the model's parameters and other input data is calculated, using a set of uncertainty levels based on the quality, range and the applicability of different sources of information. Finally, clear communication of the uncertainties and reliability of the assessment results (in a qualitative and quantitative way) is vital to create trust in the assessment results and support decision making of the pathways to achieve the predefined circularity targets.

The final phase of MSWCA is the assessment by investigating the attainability of specific circularity targets, in terms of CPIs. The goal of this phase is twofold; to assess the circularity performance of the current system and to predict by understanding potential future behavior of the system based on today's decisions (i.e. the model is run again to predict future system trajectories and assess the ability of the system to reach the circularity targets). In case that the system does not reach the quantifiable circularity targets, strategic alternative scenarios can be tested.

3.4 Circularity Performance Indicators (CPI)

The developed excel tool (Appendix A – Chapter 3) includes an indicators database for holistic circularity assessment of multi-sectoral systems, enabling information sharing for integrated management of resources. It includes requirements on data that should be measured and collected for the quantification of the CPIs.

The tool differentiates between required parameters and three types of indicators, i.e. data-oriented, information-oriented and action-oriented (i.e. CPIs) indicators. Parameters (i.e. data requirements) and data-oriented indicators (i.e. DOI) are based on information coming from different stakeholders and sources, allowing the integrated modelling of the system. Parameter is defined as a factor that can be measured or observed. DOI are indicators that can provide information on matters of wider significance or make perceptible a trend or phenomenon that is not immediately detectable (Hammond et al., 1995). The DOI can be provided by stakeholders. For example, water demand/use by sector is defined as a state indicator (e.g. by UNIDO and by European Environment Agency) for recognizing potential water conflicts. An estimation of water demand can be provided by relevant stakeholders (e.g. municipalities). Another example is the water supply service coverage or proportion of population served by the water supply industry that is defined by UNSD, 2008 as an indicator for water accessibility and its estimation can be provided by relevant stakeholders as well. Information-oriented indicators (i.e. IOI) consist of a long list of indicators that are resulted from modelling calculations – based on parameters and DOI – during the implementation of the framework and they are not directly used in, but rather support the assessment. The assessment is based on action-oriented indicators (i.e. AOI), named here as CPIs. AOI or CPIs are derived from the integrated modelling and are calculated from further processing of IOI, DOI and parameters. CPIs are used for communication of the results and consist of a short list of indicators targeted at the three CE principles to reduce the number of indicators used for circularity assessment. The IOI are indicators measuring circularity aspects indirectly and therefore, are used to explain the outcomes of the assessment. The IOI are not used for communicating the results of the assessment but they are accessible to the interested parties for informative purposes. The tool includes existing and newly-developed indicators.

The indicators tool is tailored to the multi-sectoral system approach by differentiating between whole-of-a-system and sector-specific indicators, i.e. indicators related to the system as a whole, and to the urban water, agro-food, energy, industrial, waste handling sectors and natural capital. The tool also provides information about the units, methodological aspects (i.e. methodology, equation, or reference in order to calculate the indicator), typology (differentiating between descriptive, efficiency and performance indicators), level of measurement (i.e. a 1st level indicator is a value derived from parameters, a 2nd level indicator is derived from further processing a 1st level indicator into an equation or model, and so on), description and goal of the indicator. The indicators are further categorized based on the type of information they provide, i.e. generic, economic, information related to water, nutrients & substances, energy, biodiversity, and information related to the CE principles. Regenerate Natural Capital and

Design Out Waste Externalities principles contain consequential CPIs, while Keep Resources in Use principle is measured with intrinsic CPIs.

3.5 Conceptual example – a circular city

The MSWCA framework is applied in a conceptual example of a small city. The imaginary city's electricity source is from renewables (i.e. solar and wind energy), the urban water sector consists of centralized water supply to meet the drinking water demands of the area using a surface natural resource, centralized wastewater treatment receives only blackwater, while greywater from the sinks and taps is treated separately (decentralized greywater treatment) and in combination with rainwater harvesting is used to meet the domestic demands (i.e. toilet flushing, washing machines and irrigation of gardens). The centralized wastewater treatment is performed in one treatment plant and the treated effluent (after disinfection) is sent to a set of natural and humanmade wetlands. The wetland system supplies the local agricultural water requirements. The agro-food sector consists of agriculture (both livestock and crops) and the agricultural production is sold in local markets. The waste handling sector receives the produced sludge, which is composted and used as soil amendment, while livestock manure, food and green waste are composted and sent back to agriculture for fertilization purposes. All other types of waste are disregarded in this example.

The required information is collected in the form of parameters and data-oriented indicators via the proposed Indicator Tool. The configuration of the multi-sectoral system is illustrated in Figure 3.4.

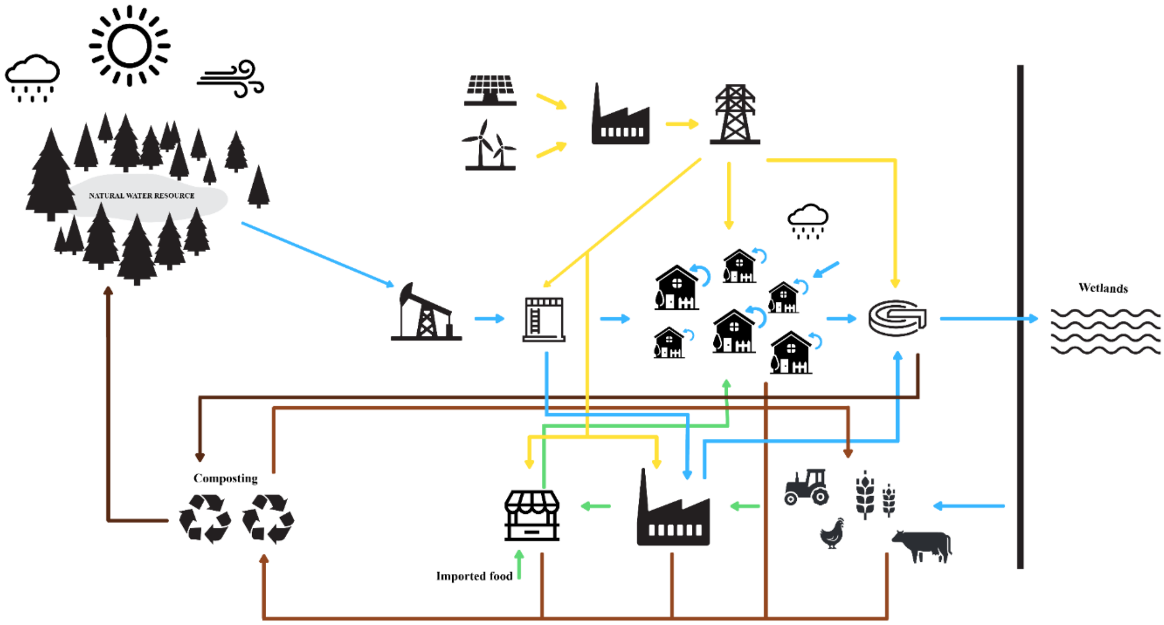


Figure 3.4: Configuration of the system

The next step of the framework includes the development of the integrated model. Parameters and data-oriented indicators are used as inputs to the model. For each one of the socio-economic and non-economic sectors, mass balances are developed and model inputs are used to calculate all the required resource flows and to solve the developed mass balances for all the incorporated resources.

For the urban water sector, daily water rates – for water treatment, use, greywater and blackwater production, treatment, recycling and discharge – are used in combination with precipitation data and catchment area (for rainwater harvesting), water resources, permanent and seasonal population, centralized and decentralized water users to calculate all the daily water flows in terms of inputs from the natural environment (i.e. water withdrawals from the natural resource, harvested rainwater), internal recirculation (for domestic water requirements), storage (in case of excess water), and outputs to the natural environment (discharge to the wetlands, leakages, and irrigation of gardens). The nutrient flows of the urban water sector are calculated based on data from nutrient concentrations in raw water, blackwater and greywater, on the incorporated water volumes, and treatment rates. The calculations result in daily nutrient inputs (from the natural environment and the agro-food sector), internal recirculation (i.e. nutrients incorporated in the recirculation of domestic water), storage and outputs to the environment (in terms of emissions and discharge or disposal) and to waste handling sector (nutrients in sludge). Water flows are also accompanied with other critical substances (e.g. chemicals used for treatment, pathogens and other pollutants) and their flows are also calculated based on their concentrations in water, waste or usage rates. The energy consumption in centralized and decentralized water and wastewater treatment are also calculated.

For the agro-food sector, nutrient and water flows incorporated in the local agricultural production are calculated based on hydro-biogeochemical modelling using soil condition, soil type and formations, hydraulic conditions, management practices, weather data, fertilizer inputs, etc. The quantification of water (e.g. infiltration, evapotranspiration, irrigation, runoff, etc.) and nutrient (e.g. nutrient surplus, nutrient in crops, nutrient in residuals, gaseous emissions etc.) flows are the modelling outputs. The local market receives locally produced food yields and imported food. The green and food waste resulted in the agro-food sector, as well as the nutrient content in the waste are also calculated. The energy consumption is calculated as well.

For the waste handling sector, daily inputs of sludge and manure, green and food waste received as well as their nutrient content are calculated. The outputs include daily amount of produced compost to be recirculated to the agricultural sector and to the natural environment, nutrients amounts in the produced compost, and nutrient outputs diluted in produced wastewater (in case of dewatering) and fate, nutrient emissions, nutrient leakages, nutrients in residual waste from screening and fate, water vapor, etc. Energy requirements are calculated as well.

Hydro-biogeochemical modelling is deployed to reveal the state of the natural environment in terms of nutrients and water cycles, soil condition and biodiversity as well. The quantification of water (e.g. infiltration, evapotranspiration, water withdrawals, runoff, etc.) and nutrient (e.g. nutrient surplus, nutrient in crops, nutrient in residuals, gaseous emissions etc.) flows are the modelling outputs, as well as the state of soil and biodiversity condition, quality and quantity of water bodies, and air quality or emissions. All the quantified final outputs of the human system model serve as inputs to the natural system model, while the calculated natural capital flows leaving the natural environment, re-enter the human system model.

The economic simulation is based on economic valuation of market and non-market services and is run in tandem, revealing economic changes in values (either positive or negative) due to the behavior of the physical multi-sectoral system.

The final step is the integration of all the different models by using developed equations, functions and rules that describe the feedback loop and socio-economic nodes. These nodes determine the amount and frequency of the resource flows entering and leaving each modelling component. The integrated system model is run, solving the whole-of-a-system daily, seasonal and annual mass balances and revealing potential changes to the natural capital due to fast processes. This is the completion of the first simulation loop. Sensitivity and uncertainty analyses are performed to investigate the uncertainty of the modelling outcomes and communicated to the relevant parties.

After ensuring the computability of the integrated model, the information-oriented indicators that were not used to solve the mass balances and the action-oriented indicators are calculated. In this conceptual example, some of the IOI that are used to solve the water balances in the integrated modelling procedure include rainfall volume, infiltration, evapotranspiration, runoff, change in soil moisture, water demand per sector, actual irrigation water demand, and others. However, the IOI of irrigation efficiency is not required to solve the water balances, but it is further calculated – as a ratio of water supplied for irrigation per actual irrigation demand – to evaluate if the agricultural system is overwatered, underwatered, or sufficiently irrigated. Similarly, the AOI of regenerative capacity index for water requires further calculation; the total quantitative and qualitative water withdrawals of the system are compared to the natural water recharge (volume of water of improved quality that is stored to the water bodies due to natural hydrological water cycle) taking also into consideration the volume of water (of the same quality) that is returned to the water bodies from the anthropogenic water system.

After having calculated all the IOI and AOI/CPIs, the results are presented and assessed. The first step of the assessment is the presentation, analysis and evaluation of the CPIs. The analysis reveals the extent of achieved intrinsic circularity of the different resources, the consequent environmental and economic effects, the synergies and antagonisms between the different sectors in terms of resources consumption and circularity and the identification of hotspots (both current and future). After the identification of system's hotspots, the relevant information-based indicators (i.e. the ones connected to the CPIs) are analyzed to understand the reason of system's failure and what actions are required to improve circularity. The reasons might be technical, physical, economic, social, regulatory or policy and they should be communicated to the relevant parties to take appropriate actions. For example, if one of the identified hotspots is the gross P balance, IO indicators related to P cycling are analyzed to understand if the reason is overfertilization, low retention capacity of soil, overwatering, etc. Or if water stress is severe, IO indicators of environmental water use, environmental water requirements, water provisioning capacity, alternative water use, internal and intersectoral water recycling, water intensity, water demand requiring drinking water standards, etc. are further analyzed to understand the reason of failure. The analysis is performed internally and only the most probable reasons of failure are presented to the relevant stakeholders.

3.6 Summary of main findings

To address water circularity, fundamental changes are needed in the way water is managed and valued, and in the way, data is shared among practitioners, policies, regulations and assessment frameworks. The proposed MSWCA framework approaches circularity from a multi-sectoral perspective following a systems approach that symbiotically manages key water-related socio-economic and non-economic sectors. A visualization of the MSWCA's application to a fictional city is presented to enable the understanding of the framework and its practical use.

Whilst developing the MSWCA framework, we identified a number of hurdles. The consistency and valid flow of input information is one of the identified hurdles. To overcome this problem, we suggest the indicators tool. The tool establishes a common baseline for data requirements and indicators to be used for the assessment. The next identified issue is the economic valuation of nonmarket goods. To overcome this issue the MSWCA framework suggests the use of both revealed and stated preference methods. The third issue relates to feedback loops and interdependencies between different sectors and the natural environment. This framework offers a novel methodology to link natural environment to human system models. Integration also entails seamless data exchange between different system components, making data interoperability a necessity. The MSWCA framework provides the environment for the interaction of data from multiple sources thus facilitating integrated modelling integration. Increased data volume and modelling complexities creates uncertainties, the proposed framework also suggests qualitative and quantitative methods to manage uncertainty in the framework.

4. Validating Circular Performance Indicators: The interface between Circular Economy and Stakeholders

4.1 Introduction

During the last decade, the concept of Circular Economy (CE) is seeing a rising popularity among policy makers, industrial and academic communities, as a prominent approach to operationalization of sustainable development (Kirchherr et al., 2017). Although the CE terminology is divergent with the existence of 120 definitions (Friant et al., 2020), the tenet of this concept is a perceived alleviation of both economic and natural capital scarcity (Lonca et al., 2018). To enable a CE transition, corporate bodies and organisations have developed principles on which CE should be founded (e.g. regeneration of natural environment; keep resources in use; and design out negative externalities) (Arup et al., 2018). CE – as a response to the current linear economic model of "take-make-dispose" – has shaped many political and strategic research agendas both in Europe (e.g. United Kingdom, Netherlands, Sweden among others) and worldwide (e.g. China) (Korhonen et al., 2018). In fact, the European Union founds its recovery strategy from the COVID-19 on the EU Green Deal and the New Circular Economy Action Plan (CEAP) (EC, 2021). In the new CEAP (EC, 2021), water, food and nutrients are approached as a nexus, which is identified as one of the key value chains requiring urgent, comprehensive and coordinated circularity actions.

The increased traction of CE indicates the urgent need for a common circularity assessment framework and a metric system, capable of holistically and systemically measuring and evaluating CE actions. Working in this direction, many studies have focused on the identification and development of CE indicators at different implementation levels (i.e. nano, micro, meso, macro), different economic sectors, and addressing different CE aspects. Some examples include: 22 macro-level and 12 meso-level indicators introduced by Geng et al. (2012), 28 company-level indicators proposed by Pauliuk (2018), 10 sustainability related CE indicators suggested by Helander et al. (2019), 10 macro-level indicators, including 16 sub-indicators proposed by EC (2018b), and many more. In total, Kravchenko et al. (2020) identified 270 CE indicators existing in the literature. These findings suggest the great complexity of measuring CE as it involves the synthesis of multiple aspects, the consideration of sector-specific challenges resulting from specificities of different sectors (EC, 2015a), as well as the incorporation of different visions and needs of various stakeholders at different implementation levels. Focusing on water, it is not only the specificities of the water sector that need to be considered but rather the specificities of the nexus as mandated by the new CEAP. In a resource nexus, numerous factors and functional elements need to be considered (Serrano-Tovar et al., 2019), leading to additional interactions that need to be investigated, which further increases the complexity of implementing, measuring and assessing circularity.

As the concept of CE is becoming an integral component towards sustainable business practice (Kopnina and Blewitt, 2018), specific action plans have been developed (e.g. EC, 2015a and EC, 2020) to enable this transition. The progress of CE actions is supported and measured by CE indicators (Moraga et al., 2019), which need to be comprehensive and to meet the needs of CE participants, i.e. individual companies and industry, society and the nation (Banaitė et al., 2016; Sánchez-Ortiz et al., 2020). Therefore, apart from the relevance of CE to policies, regulations and legislation, CE strategies need to be integrated into business practices that mandate for the operationalization of the concept for organizations (Lieder et al., 2016). Since the concept of CE is a new scientific research topic, in many cases, companies and industry lack of in-depth knowledge of CE benefits and drawbacks to businesses and society, indicating that businesses cannot propose solutions to CE problems (Bocken et al., 2017). Targeted guidance on CE implementation, monitoring and evaluation is still needed, the lack of which may further implicate the indicators selection process by organizations (Pauliuk, 2018). The water industry and related CE practitioners therefore need guidance and in-depth information regarding appropriate circularity indicators for the nexus. Park and Kremer (2017) state that companies lack information on the usefulness of existing indicators that reduces and hinders their practical applicability. Additionally, each company, stakeholder or actor that intends to apply sustainable measures – or in this case circularity measures – has different concerns, needs, opportunities, goals and risks (Waas et al., 2014). Therefore, the assessment process should match these requirements and limitations in order to increase its meaningfulness and implementation (Roos Lindgreen et al., 2020). However, the individual needs of organizations should not overcome the CE fundaments as this would allow businesses to select indicators based on their own marketing purposes, discrediting CE as another form of greenwashing (Harris et al., 2020).

Recent studies focus on shedding light to classification, purpose and possible uses of various CE indicators (e.g. in Saidani et al., 2019 and in Moraga et al., 2019) to enable decision-making. However, these studies do not provide information regarding the influence and the interrelationships between indicators. Such information would enhance the understanding on indicators behaviour and would enable the investigation of indicators importance, contributing to the selection process. This is particularly important for indicator sets targeting nexuses or other complex systems that require numerous indicators interfering with each other. Multi-criteria decision-making approaches can be used for this purpose. For example, Yadav et al. (2020) used a hybrid Best Worst Method (BWM)-DEcision MAking Trial and Evaluation Laboratory (DEMATEL) approach to analyse the causal relationship of CE indicators for the manufacturing sector. Although DEMATEL method enables the investigation of relationships between the factors of a complex system, it cannot be used to establish structural hierarchy among the investigated factors. In cases where prioritization of factors needs to be established, Interpretive Structural Modelling (ISM) is the preferred methodology. The ISM method does not require quantitative data and in general has reduced data requirements compared to other similar methods (Panigrahi and Sahu, 2018). The ISM method is an interactive learning process used to determine the mutual interactions and relationships between various factors that influence the system (Bouzon et al., 2015).

In this study, a closer collaboration between science and practice for a dynamic indicators' selection process is suggested that is based on scientific and participatory approaches, ensuring the application of a meaningful set of CE indicators without compromising the principles of CE. A combined expert and participatory approach to CE indicators selection would enable the relevant stakeholders and practitioners to make more informed decisions based on representative indicators that they have critically prioritized. The stakeholders' involvement to the participatory process is further expected to increase the adoption and uptake of holistic and systemic assessment to CE (Roos Lindgreen et al., 2020).

The aim of this research is to provide a multi-criteria decision-making methodology that can be applied in various sets of indicators in order to enable the selection of appropriate CE indicators, considering both the specificities of the sectors, the practical needs and the scientific knowledge. In this case, the suggested methodology is applied in the Water-Energy-Food-Ecosystems (WEFE) nexus and uses the CE indicators developed within the Multi-Sectoral Water Circularity Assessment (MSWCA) framework (Nika et al., 2020b). The indicators are ranked by industrial stakeholders and researchers in order to consider both the practical needs of the industry and the scientific consensus of CE. An Interpretive Structural Model (ISM) is then developed enabling the identification of interdependencies among the indicators and

MICMAC analysis is further deployed classifying the indicators based on their driving and dependence power. MICMAC analysis is used to recognize the driver and reliance of inhibitors to transparency applying the ISM approach (Sushil, 2012). The suggested methodology enables the development of a structural understanding of the direct and indirect interrelationships between the specific CE indicators, as well as their prioritization based on the derived hierarchical structure. It provides the CE practitioners with a novel approach to strategically identify relevant indicators, understand behavioural aspects and the interactions between target indicators and ultimately use suitable CE indicators based on a multi-criteria decision-making process.

The study is structured in five sub-chapters. In the following sub-chapter (4.2), an analysis of the selected list of Circularity Performance Indicators (CPIs) is presented. Sub-chapter 4.3 describes the ISM approach and MICMAC analysis used in this study. Sub-chapter 4.4 then presents and discusses the results and explores the implications of this study. Conclusions are drawn in the final sub-chapter (4.5).

4.2 Identification of CE indicators

The MSWCA is a framework developed to guide the implementation, monitoring and assessment of CE in systems under the WEFE nexus. CE in nexus systems is not thoroughly investigated, while CE in water systems mostly focuses on circularity measures, strategies and actions targeted at the wastewater treatment plants, underestimating circularity potential of upstream processes. The MSWCA approaches circularity from a systems perspective, targets the symbiotic management of various resources incorporated in the nexus, considers the interactions between the various sectors involved in the investigated systems and integrates the anthropogenic and natural sub-components of the system. This allows the investigation of the feedback loops between the human-managed and nature-managed systems, which may influence the circularity results. The framework develops an indicators database that includes data requirements and a thorough list of available indicators relevant for nexus systems at the macro-level to support data acquisition and CE assessment. The database serves as an initial step for the identification of appropriate indicators by providing insights on the different aspects that must be covered by circularity evaluations of nexus systems (e.g., economic, environmental, physical), the different resources, the sectors' specificities, the CE principles.

The indicators database differentiates between whole-of-a-system and sector-specific indicators, i.e., indicators related to the system as a whole, and to the urban water, agro-food, energy, industrial, waste handling sectors and natural environment (i.e., non-economic sector). The indicators are divided into Information-Oriented Indicators (IOIs) and Action-Oriented Indicators (AOIs or CPIs). The IOIs consist of a long list of indicators per each socio-economic and non-economic sector and they are categorized based on the type of information they provide, i.e., generic, economic, information related to water, nutrients & substances, energy, biodiversity. The IOIs serve as an intermediate step, connecting the acquired data to the CPIs and result from the first itineration of calculations, providing detailed information regarding the different aspects for each component of the sectoral supply chain. The IOIs are not directly used for the circularity assessment of the system, but rather support the assessment as they give meaningful information for the interpretation of the outcomes.

The circularity assessment of multi-sectoral systems is based on the CPIs. The CPIs are derived from grouping different IOIs and they are used for communication of the results to the different stakeholders. CPIs consist of a short list of indicators – 23 in total – targeted at the three CE principles in order to reduce the number of indicators used for circularity assessment. Therefore, information overload – regarding the results communicated to the different interested parties – is avoided but at the same time, access to IOIs offer the possibility of understanding underlying factors, processes, or interactions that are linked with circularity. However, each system under investigation is unique and may be composed by different components and different processes may be involved. Therefore, the suggested indicators may be modified based on the system's requirements, purpose and specificities.

This research focuses on the evaluation, ranking and investigation of the interrelationships between the developed CPIs. The CPIs are presented and explained in the following section. The categorization of the CPIs according to the CE principle that they target is adopted by Nika et al., 2020b. Therefore, the regeneration of natural environment principle aims to ensure a good environmental state and functional environmental flows and stocks. The keep resources in use principle aims at closing the resource loops of the system, while the design out negative externalities principle targets the reduction of negative impacts potentially caused by the system by turning them into positive outcomes. Since waste and emissions cause a negative impact that is not incurred by their producer, actions taken to reduce or reuse waste or emissions are evaluated under the design out negative externalities principle.

4.2.1 Indicators related to the regeneration of natural environment principle

Gain/Loss of (semi-)natural areas

Semi-natural and natural areas represent the environment where natural ecosystems can be developed and thrive, and provide a wide range of ecosystem services to people (Grima et al., 2020). From a social point of view, access to natural or semi-natural areas has been linked to mental health benefits (Bratman et al., 2019), reduced stress (Bratman et al., 2012), physical health benefits (Eigenschenk et al., 2019), increased life expectancy (Takano et al., 2002), improved social relations (Hartig et al., 2014), increased social cohesion (Hartig et al., 2014), reduced violence and aggressive behaviour (Kuo and Sullivan, 2001), and improved well-being and welfare (Kaplan, 2001).

This indicator requires the quantification of changes in land use land cover prior and after the implementation of CE measures. This quantification would indicate the state of (semi-)natural areas, enabling the evaluation of the impacts of the economic development on both the environment and the society, as well as the evaluation of sustainable management and utilization of natural resources.

Regenerative capacity index

This indicator serves as a comparison between the anthropogenic exploitation of natural resources (i.e. the rate/amount of natural resource extraction) and the capacity of nature to regenerate itself (i.e. the rate/amount of resource regeneration by nature). The indicator is inspired by the Planetary Boundaries concept (Rockström et al., 2009) and their transferability to regional systems (Dearing et al., 2014) and requires the quantification of "safe operating space limits" for nine natural processes – i.e. climate change, rate of biodiversity loss (terrestrial and marine), interference with the nitrogen and phosphorus cycles, stratospheric ozone depletion, ocean acidification, freshwater use, change in land use, chemical pollution, and atmospheric aerosol loading – at a local level. These "safe operating space limits" represent the critical natural thresholds, which – if crossed – would trigger an irreversible environmental change. Quantification of such regional thresholds would indicate the natural limits under which CE should operate. This indicator incorporates a social aspect as well, since crossing regional-specific tipping points may have severe impacts on humanity.

Carbon balance

The carbon balance indicator is based on mass balances and allows for the detection and quantification of carbon added to or extracted from the atmosphere in the form of carbon dioxide. Both natural (e.g. carbon sequestration by soils and vegetation) and human activities (e.g. fossil fuel combustion) are considered when quantifying this measure. The quantification of this indicator can be achieved by utilizing either analytical tools – such as Carbon Footprint Accounting and Life Cycle Assessment – or biogeochemical modelling tools, which are more complex but enable a dynamic interpretation of the system (Nika et al., 2020a). This indicator allows both human-managed and natural-managed processes to be considered.

Nitrogen and phosphorus balance

The gross nitrogen balance and the gross phosphorus balance are two agro-environmental indicators used by European Statistical Office (EUROSTAT). Similarly to the carbon balance, this indicator quantifies nitrogen inputs and outputs and their difference results in the gross nitrogen surplus (GNS), indicating potential nitrogen losses to the environment (e.g. ammonia emissions, nitrate leaching, nitrous oxide emissions). On the other hand, if outputs outweigh the inputs, a nitrogen deficit is occurring, indicating potential risk of decline in soil fertility. The gross phosphorus balance follows the same approach for its quantification. However, the actual risk of phosphorus losses to the environment depends on various local factors, such as climate conditions, soil type and characteristics, management practices, etc.

Water stress

Water stress is a widely known indicator that compares the freshwater demand to the available amount of freshwater resources for a specific period of time. The freshwater availability is defined considering both the water quantity and quality since reduced water quality is a major factor restricting its use. Freshwater supplies deteriorate as a result of water stress, such as dry rivers, eutrophicated lakes, and seawater intrusion into aquifers, and have major consequences for humans, habitats, and economic activities. There are many methodologies for quantifying this measure in the literature.

Hydrological performance

The hydrological performance indicator – adopted by Renouf et al. (2017) – investigates the local water balance considering both natural and anthropogenic processes and estimates the produced runoff, evapotranspiration and infiltration of the system. Reduced evapotranspiration contributes to the heat island effect, and reduced infiltration reduces aquifer recharge. Increased runoff raises the risk of flooding and degrades the health of freshwater resources; reduced evapotranspiration contributes to the heat island effect; and reduced infiltration reduces aquifer recharge. As a result, decreased hydrological efficiency will have a negative effect on local habitats, as well as a reduction in some key ecosystem services.

Qualitative water withdrawal reduction

Qualitative water withdrawals (i.e. reduced water quality) form the second aspect that contributes to water stress and has significant impacts on people, ecosystems and economy. The main contributor to reduced water quality is the production, inadequate treatment and discharge of municipal, industrial and agricultural wastewater. Monitoring and sampling campaigns on local freshwater resources would enable the evaluation of water quality improvements due to CE measures in the area of interest.

Soil condition improvement

Soil condition is defined as "the capacity of a soil to function, within land use and ecosystem boundaries, to sustain biological productivity, maintain environmental health, and promote plant, animal, and human health" (Doran and Zeiss, 2000). Therefore, soil condition plays a key role in maintaining healthy ecosystems and providing ecosystem services. Soil condition improvement is particularly relevant for CE measures implemented on economic activities that have a direct impact to and/or are impacted directly by soil, e.g. agriculture. Soil condition and its improvement by CE measures can be measured using soil sampling campaigns and soil monitoring protocols.

Index of biodiversity

As biodiversity has been declining at an alarming rate, the Global Economic Forum ranks biodiversity loss as one of the top five global risks in terms of likelihood (World Economic Forum, 2020). The main contributors to biodiversity loss are land use change, pollution, species overexploitation, climate change and invasive species and diseases (WWF, 2020). Therefore, CE measures aiming to reduce pollution and tackle climate change should have a positive impact to biodiversity restoration. Several protocols exist in the literature to measure biodiversity.

Revenues/Savings from natural capital regeneration

This indicator focuses on ecosystem accounting (Uhel et al., 2010) by assigning monetary estimates to ecosystems and their services in order to capture the value of both natural capital and the impacts of its loss. Ecosystem accounting distinguishes between ecosystem services that are directly used by people – using both market and non-market valuation approaches – and services that support ecological functions, which is estimated based on the costs of ecosystem's restoration and maintenance. Ecosystem accounting enables the estimation of costs to the society that derive from changes in ecosystems, expressed in monetary terms or in relation to health and livelihood risks. CE should be able to reduce these costs and turn them into revenues.

4.2.2 Indicators related to the keep resources in use principle

Circular use

The Circular Use (CU) indicator is adopted by Enel S.p.A. (2018) and considers the measures taken to extend the time of use of an asset. Extension of the use time of an asset can be achieved by design and maintenance improvements that would increase the useful life of the product, by product sharing and by selling services and the outcomes of a product rather that the product itself (i.e. service as a product). Such measures may potentially result in environmental benefits by reducing the consumption of materials and resources.

However, there are some products that are neither designed nor manufactured – e.g. water – and therefore, such measures are not directly applicable. In the case of water, the World Business Council for Sustainable Development (WBCSD, 2021) developed a similar indicator, namely "Onsite circulation" that calculates the total amount of reused water onsite.

Circular flow

The Circular Flow (CF) indicator (Enel S.p.A., 2018) is based on mass balances and accounts for all inputs and outputs of the system. This indicator is further split into two sub-indicators –

following the approach of WBCSD (2021) – namely, "Circular Input Flow" and "Circular Output Flow". Circular Input Flow is defined as the ratio of all circular inputs (i.e. input from recycle, reuse, renewables, reduction, etc.) to the total inputs, including inputs from non-renewable resources and virgin materials. Circular Output Flow is defined as the ratio of all effectively utilized outputs (i.e. output sent to recycle, output sent to reuse, output included in the final product, etc.) to the total output, including waste disposal. The average value of these two sub-indicators result in the value of the Circular Flow indicator.

Circular index

Circular Index (CI) (Enel S.p.A., 2018) combines Circular Use (CU) and Circular Flow (CF) indicators in the following equation:

$$CI = CF + \frac{(1 - CF)\ x\ (CU - 1)}{2\ x\ CU} \tag{4.1}$$

This indicator can be applied to all incorporated resources (e.g. water, energy, nutrients, etc.), materials, and (by-)products of a system.

Maximum achievable circularity

Maximum achievable circularity is an aspirational indicator, estimating the resource/material demand that can actually meet its requirements by using alternative/circular sources over the total system's requirement of this resource/material. This indicator aims to account for the system's demands that are restricted by regulations or market specifications (e.g. strict quality of products, materials, etc.) and thus, cannot meet their requirements by using alternative sources, indicating that in such cases the value of the circular index indicator could never reach 1. A value equal to 1 would indicate a closed resource/material loop. For example, water for potable uses cannot meet its requirements by using recycled water due to strict regulations.

However, this indicator is also influenced by the regenerative capacity index. For example, if a water system operates under safe water limits, then the water requirement for potable uses is considered to be circular and thus, the maximum achievable water circularity of the system can be equal to 1.

Therefore, if a circularity assessment restricts its boundaries to the human-managed system only, the maximum achievable circularity of strictly-regulated resources/materials/products cannot be 1, while if the nature-managed system falls under the system's boundaries then the value of this indicator can potentially reach its maximum value.

Revenues/Savings from circularity measures

This indicator estimates the monetary impacts of the circular index, excluding the revenues/costs from both *natural capital regeneration* and *design out negative externalities* (explained in the following sub-section). Capital and operational costs are included to the estimation of the revenues. This indicator can take various forms from a pure monetary unit to a ratio of revenues/savings before and after CE implementation, etc.

4.2.3 Indicators related to the design out negative externalities principle

Product index

Product index is an indicator developed by Villarroel-Walker et al. (2009) and measures the resources consumed that are returned to the system as a useful product. This indicator is based on the principle of waste equals food, indicating that in an eco-effective system (i.e. an ideal system) there are no generated emissions and all produced waste is utilized as a product by any system's component.

Waste index

Waste index (Villarroel-Walker et al., 2009) is the opposite of the product index, measuring the consumed resources of the system that are returned as a waste. In a CE, this indicator should be minimized.

Total waste reduction

This indicator is a direct measurement of the avoided waste due to CE measures and it is based on mass balances. Complementary to this indicator is the waste eco-efficiency index (Villarroel-Walker et al., 2009), which accounts for the value gained by the products of the system (in mass/volume of products) compared to the total unutilized waste of the system, i.e. waste that is disposed.

Total emissions reduction

Total emissions reduction is similar to the previous indicator but it accounts for the actual emissions (i.e. substances or compounds of interest). In CE, emissions should be either reduced or effectively utilized by any natural or anthropogenic system's component. The value gained by the system's products compared to the total generated and unutilized emissions, can provide additional useful information in this case as well.

Revenues/Savings due to minimization of negative externalities

This indicator estimates the economic impacts of CE by reducing the negative externalities that are created from the linear system. The indicator is mainly based on non-market evaluation methods, avoiding double counting with the economic-related indicator of the natural capital regeneration. Subsidies and other similar economic incentives should be accounted in this indicator.

4.3 Methods

In this section, the developed questionnaire used to validate the indicators, as well as the methodological steps for the ISM approach and MICMAC analysis are presented and analysed.

4.3.1 Questionnaire design and validation of indicators

Evaluation and validation of the CPIs was performed by surveying purposely-selected stakeholders from academia, as well as from public and private agencies – i.e., water utility companies, agri-food industries, local authorities and consultancy companies – with direct and indirect roles in the different sectors. Purposeful sampling is a sampling technique widely used in qualitative research in order to identify and select information-rich cases (i.e., individuals with special knowledge and experience) related to the research topic (Patton, 2014; Creswell and Clark, 2011). Purposeful sampling often involves a small number of participants (Palinkas et al., 2015), for example similar studies using purposeful sampling involved 32 individuals (Sarabi et al., 2020) and 16 stakeholders (Renouf et al., 2017). Therefore, the stakeholders involved in the survey (both academic and industrial stakeholders) were individuals actively involved in the concept of CE in the WEFE nexus.

The surveys were conducted via an online questionnaire for the public and private stakeholders and via an online workshop for the academic stakeholders – participating in the COST Action

CA17133 Circular City. The virtual workshop was conducted using Mural digital workspace, which was designed in the same way as the online questionnaire for the industrial stakeholders. Thus, academic and industrial stakeholders were asked the same questions. After the completion of the Mural session, a discussion between the experts was performed to better understand their views on the topic. The selected stakeholders and academics were asked to evaluate the importance of each CPI using a three-point scale rating from Low (1) to High (3). In total, 40 questionnaires were completed from 17 countries. The designed questionnaire and the responses can be found in Appendix B – Chapter 4.

Using stakeholders' opinions to validate CPIs is an important and necessary activity. Indicators need to resonate with stakeholders, so that they can be properly used by them (Falck and Spangenberg, 2014). Including stakeholder participation in CPIs validation process is a robust way of representing the different stakeholders' opinions, perceptions, values and concerns (Mascarenhas et al., 2015). This approach combined with the interpretive structural modelling (ISM) offers analytical insights into the relevance and usefulness of the CPIs based on stakeholder representativeness and data availability, and is scientifically rigorous. The results from such a combined approach can influence stakeholders decision-making processes and support the development of a common way of evaluation by all relevant stakeholders.

Table 4.1 presents the results of the CPIs ranking as obtained by the conducted interviews. The responses per indicator were averaged, considering both the answers of industrial stakeholders and academics.

Table 4.1: Ranking of CPIs by industrial & academic stakeholders; Colour labels: Yellow – CPIs for Design out negative externalities, Blue – CPIs for Keep resources in use, Green – CPIs for Regeneration of natural environment

Rank	Ranked Indicators for Circularity Assessment	Average Value
1	Total Waste Reduction (I1)	2.76
2	Circular Index (I2)	2.72
3	Revenues/Savings from Circularity Measures (I3)	2.72
4	Revenues/Savings due to Minimization of Negative Externalities (I4)	2.67
5	Circular Use (I5)	2.65
6	C balance (I6)	2.60
7	Circular Flow (I7)	2.59
8	Water Stress (I8)	2.58

9	Maximum Achievable Circularity (I9)	2.50
10	Regenerative Capacity (I10)	2.44
11	Product Index (I11)	2.44
12	Waste Index (I12)	2.44
13	Total Emissions Reduction (I13)	2.42
14	Qualitative Water Withdrawal Reduction (I14)	2.39
15	Revenues/Savings from Natural Capital Regeneration (I15)	2.39
16	Gross P & N balance (I16)	2.31
17	Gain/Loss of (Semi-)Natural Areas (I17)	2.29
18	Hydrological Performance (I18)	2.26
19	Soil Condition Improvement (I19)	2.19
20	Index of Biodiversity (I20)	2.06

Based on the results of Table 4.1, waste reduction (I1) and circular index (I2) are evaluated as the most important CE indicators by the stakeholders, followed by the economic-related indicators of revenues/savings from circularity measures (I3) and revenues/savings due to minimization of negative externalities (I4). In general, indicators related to the keep resources in use and the design out negative externalities principles are perceived as more important compared to the indicators related to the regeneration of natural environment principle with the exception of carbon balance (I6) indicator probably due to its direct connection to global warming and climate change. The outcome is in line with the conclusion of some scientific studies that postulated that CE is mostly perceived by a technocentric perspective with reduced focus on the actual benefits to the natural systems and society (Friant et al., 2020; Harris et al., 2020). All indicators received a good ranking (above 2), indicating that the participants are interested in all selected indicators. Therefore, all the selected indicators are included to the Interpretive Structural Modelling procedure.

4.3.2 Interpretive structural modelling (ISM)

ISM is a well-established methodology for identifying the interactions between different interlinked factors involved in complex problems. The various direct and indirect interactions between different factors enable an accurate description and understanding of the problem, rather than focusing on each factor individually. ISM analyses the influence of one factor over all the others, by decomposing them into different levels and imposing order and direction on the complexity of their relationships. In complex indicator systems as the ones mandated by nexus approaches, the application of ISM would enable a better understanding and prioritization of the incorporated indicators based on their structural hierarchy. The development of indicators' importance levels would enable practitioners and relevant stakeholders to better understand the indicators behaviour, facilitating the selection process.

ISM has been applied to understand the relationships between indicators in various studies. For example, Tseng (2013) used ISM to analyse the interactive relations of sustainable production indicators, Amrina et al. (2019) and Amrina et al. (2020) identified the most influencing indicators related to sustainable maintenance performance in the rubber and cement industry, respectively, while Gardas et al. (2019) investigated performance indicators of green supply chain management in agro-industry. In this study, the application of ISM enables the establishment of interrelationships between the different CPIs, as well as the identification of those indicators that have high driving power, requiring the consciousness of decision makers. ISM is chosen as a simple method that does not depend on the intensity of the relationship between the indicators but it only requires the dominance level (Sarabi et al., 2020).

ISM begins with the identification of relevant variables to the problem or question, and then progresses to a group problem-solving technique. Then a subordinate relation that is contextually appropriate is chosen. After deciding on the element set and contextual relationship, a structural self-interaction matrix (SSIM) is generated by comparing variables pairwise. The SSIM is then transformed into a reachability matrix (RM) and the transitivity of the RM is checked. A matrix model is obtained after transitivity embedding is completed. The partitioning of the elements is then determined, followed by the extraction of the structural model known as ISM. The various steps involved in ISM technique are illustrated in Figure 4.1 and are further analysed in the following sub-sections.

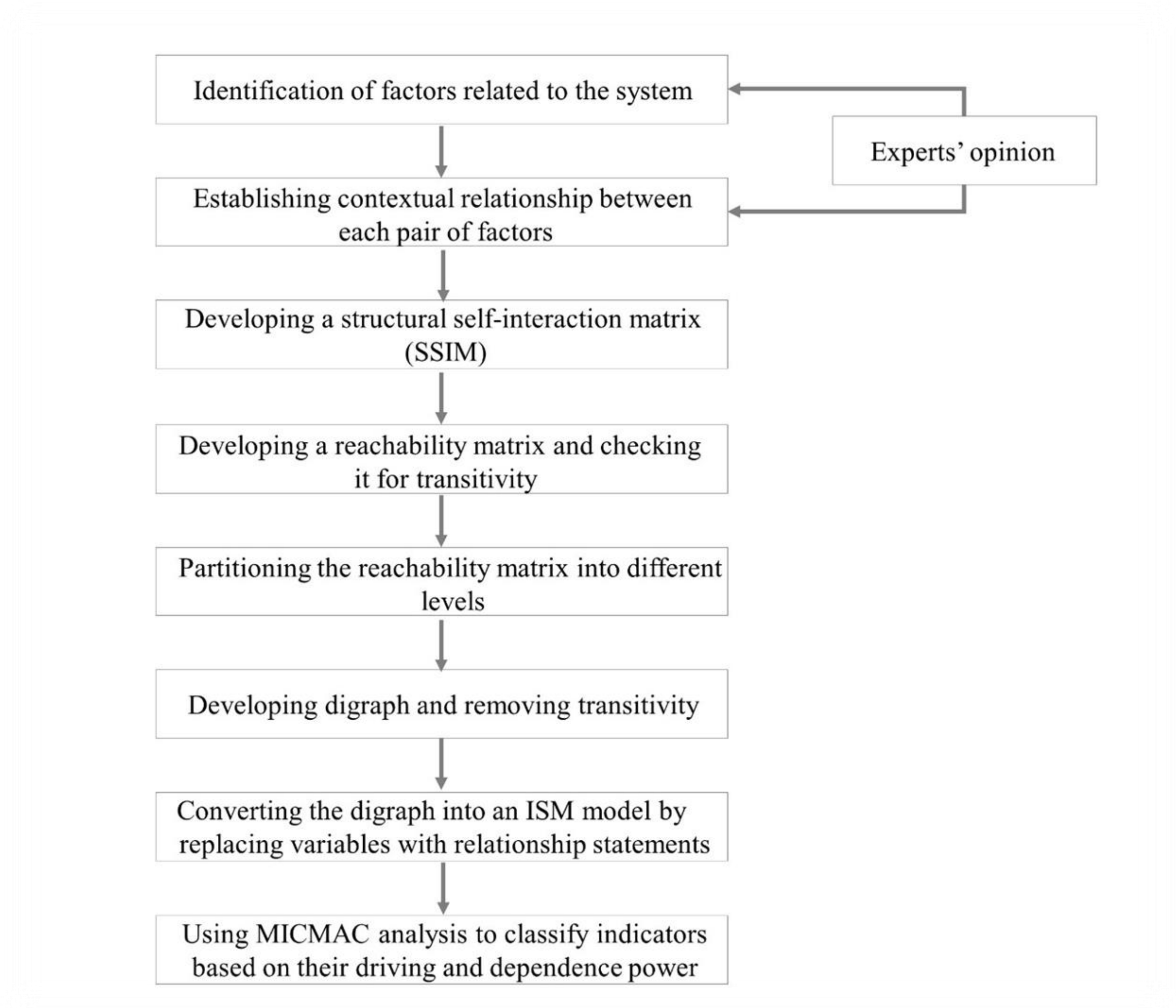


Figure 4.1: Flow diagram for preparing ISM model

4.3.2.1 Establishment of relationships and development of structural self-interaction matrix

For the identification of the contextual relationship among the different CPIs, eight experts on the field of CE having more than 6 years of experience were consulted via direct interviews. For each pair of CPIs, the experts were asked to determine the interaction of the CPIs by considering the contextual relationship of "leads to" and "influences" type. The experts' responses were averaged and the results were communicated to the same experts to finalize the direction of the relationships.

Based on the results of the experts' consultation regarding the relationships between each pair of CPIs, the structural self-interaction matrix (SSIM) is developed and presented in Table 4.2, using the following symbols:

V for the relation from indicator i to indicator j – i.e. indicator i will influence indicator j

A for the relation from indicator j to indicator i – i.e. indicator i will be influenced by indicator j

X for both direction relations – i.e. indicators i and j will influence each other

O for no relation between the indicator – i.e. indicators i and j are unrelated

Table 4.2: Structural Self-Interaction Matrix

CPIs	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	-	O	O	O	O	V	O	V	O	O	A	A	X	V	O	V	O	O	V	V
2		-	V	O	V	O	V	O	A	X	O	O	O	O	O	O	O	O	O	O
3			-	X	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
4				-	O	A	O	A	O	O	O	O	O	A	X	A	A	A	A	A
5					-	O	X	O	O	O	V	V	O	O	O	O	O	O	O	O
6						-	O	O	O	A	O	O	A	O	V	O	A	O	X	X
7							-	O	O	O	V	V	O	O	O	O	O	O	O	O
8								-	O	A	O	O	A	A	V	O	A	A	A	A
9									-	X	O	O	O	O	O	O	O	O	O	O
10										-	O	O	O	V	O	V	V	V	V	V
11											-	X	V	O	O	O	O	O	O	O
12												-	V	O	O	O	O	O	O	O
13													-	V	O	V	X	O	V	V
14														-	V	A	A	O	O	V
15															-	A	A	A	A	A
16																-	A	O	X	X
17																	-	A	X	X
18																		-	X	X
19																			-	X
20																				-

4.3.2.2 Reachability matrix and level partitions

In the next step of the ISM approach, the initial reachability matrix from the SSIM is developed, by replacing the four symbols (i.e., V, A, X or O) of the SSIM with binary numbers in the initial reachability matrix. The rules for this substitution are the following:

- If the (i, j) entry in the SSIM is V, then the (i, j) entry in the reachability matrix becomes 1 and the (j, i) entry becomes 0.
- If the (i, j) entry in the SSIM is A, then the (i, j) entry in the matrix becomes 0 and the (j, i) entry becomes 1.
- If the (i, j) entry in the SSIM is X, then the (i, j) entry in the matrix becomes 1 and the (j, i) entry also becomes 1.
- If the (i, j) entry in the SSIM is O, then the (i, j) entry in the matrix becomes 0 and the (j, i) entry also becomes 0.

The initial reachability matrix (see Appendix) needs to be tested for transitivity based on the basic assumption that if indicator A is related to indicator B and indicator B is related to indicator C, then indicator A is necessarily related to indicator C. Following the transitivity rule, some 0 values of the initial reachability matrix will change to 1. The final reachability matrix is prepared by indicating the changed values of the initial reachability matrix with 1* as illustrated in Table 4.3. Indicators in the same level across the rows and columns are clustered to calculate the drive and dependence powers. The drive power of an indicator is derived by summing up the binary numbers in the rows and its dependence power by summing up the binary numbers in the columns.

Table 4.3: Final Reachability Matrix

CPIs	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	**Driving power**
1	1	0	1*	1*	0	1	0	1	0	0	0	0	1	1	1*	1	1*	1*	1	1	13
2	1*	1	1	1*	1	1*	1	1*	1*	1	1*	1*	1*	1*	1*	1*	1*	1*	1*	1*	20
3	0	0	1	1	0	0	0	0	0	0	0	0	0	0	1*	0	0	0	0	0	3
4	0	0	1	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	3
5	1*	0	1*	1*	1	1*	1	1*	0	0	1	1	1*	1*	1*	1*	1*	1*	1*	1*	17
6	1*	0	1*	1	0	1	0	1*	0	0	0	0	1*	1*	1	1*	1*	1*	1	1	13
7	1*	0	1*	1*	1	1*	1	1*	0	0	1	1	1*	1*	1*	1*	1*	1*	1*	1*	17
8	0	0	1*	1	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	4
9	1*	1	1*	1*	1*	1*	1*	1*	1	1	1*	1*	1*	1*	1*	1*	1*	1*	1*	1*	20
10	1*	1	1*	1*	1*	1	1*	1	1	1	1*	1*	1*	1	1*	1	1	1	1	1	20
11	1	0	1*	1*	0	1*	0	1*	0	0	1	1	1	1*	1*	1*	1*	1*	1*	1*	15
12	1	0	1*	1*	0	1*	0	1*	0	0	1	1	1	1*	1*	1*	1*	1*	1*	1*	15
13	1	0	1*	1*	0	1	0	1	0	0	0	0	1	1	1*	1	1	1*	1	1	13
14	1*	0	1*	1	0	1*	0	1	0	0	0	0	1*	1	1	1*	1*	1*	1*	1	13
15	0	0	1*	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	3
16	1*	0	1*	1	0	1*	0	1*	0	0	0	0	1*	1	1	1	1*	1*	1	1	13
17	1*	0	1*	1	0	1	0	1	0	0	0	0	1	1	1	1	1	1*	1	1	13
18	1*	0	1*	1	0	1*	0	1	0	0	0	0	1*	1*	1	1*	1	1	1	1	13
19	1*	0	1*	1	0	1	0	1	0	0	0	0	1*	1*	1	1	1	1	1	1	13
20	1*	0	1*	1	0	1	0	1	0	0	0	0	1*	1*	1	1	1	1	1	1	13
Dependence power	16	3	20	20	5	16	5	17	3	3	7	7	16	16	20	16	16	16	16	16	

The determination of the importance level of each indicator is derived from the level partitions. From the final reachability matrix, the reachability and the antecedent sets are derived. The reachability set of an indicator consists of the indicator itself and the other indicators it may impact, while the antecedent set of an indicator consists of the indicator itself and the other indicators that may influence the specific indicator. Thereafter, the intersection set of an indicator derives from the intersection of the reachability and antecedent sets. The indicators that have the same intersection and reachability sets are identified as top-level indicators in the ISM hierarchy and are removed from consideration for the next levels. Top level indicators are the ones that do not influence any other indicators above their level. The same process is repeated to identify the indicators of the next level and the process continues until the importance level of all indicators is specified. In this case, the partitions level process resulted in six iterations (see Appendix) and the results of the importance level of each indicator are illustrated in Table 4.4.

Table 4.4: Importance levels of the indicators

Level	CPIs
I	I3. Savings from circularity measures
	I4. Savings due to minimization of negative externalities
	I15. Savings from natural capital regeneration
II	I8. Water Stress
III	I1. Total Waste Reduction
	I6. C Balance
	I13. Total Emissions Reduction
	I14. Qualitative Water Withdrawal Reduction
	I16. Gross N & P Balance
	I17. Gain/Loss of (Semi-)Natural Areas
	I18. Hydrological Performance
	I19. Soil Condition Improvement
	I20. Index of Biodiversity
IV	I12. Waste Index
	I13. Product Index
V	I5. Circular Use
	I7. Circular Flow
VI	I2. Circular Index
	I9. Maximum Achievable Circularity
	I10. Regenerative Capacity

4.3.2.3 Digraph and ISM model

The next step of the ISM procedure is the development of the digraph. The digraph represents the visual illustration of the indicators and their interdependencies and is generated by indicators nodes and lines of edges based on the results of the final reachability matrix and the partitioning levels. Therefore, the nodes of the top-level indicators are positioned at the top of the digraph, followed by the nodes of the second level indicators connected with arrows and so on, until the bottom level indicators are positioned at the lowest part of the digraph. The arrows represent the direct links of the indicators between the consequent importance levels. Therefore, each indicator at a higher importance level is influenced by at least one indicator at the next lower importance level. The generated digraph is converted into the ISM model by replacing the indicator nodes with statements. The results are presented and discussed in sub-chapter 4.4.

4.3.2.4 MICMAC analysis

The ISM approach is complemented with the cross-impact matrix multiplication applied to classification (Matrice d' Impacts Croisés Multiplication Appliquée á un Classment – MICMAC) in order to explore the grey area between 0 and 1. MICMAC is a structural prospective analysis used to investigate the indirect (i.e. cross-correlation) relationships between different variables and thus, it enables the selection of significant indicators in a more accurate way. MICMAC analysis is expected to provide additional valuable insights on the results of the ISM model by further identifying the complex and indirect interactions between the investigated indicators. The identification of indicators driving and dependence power enables the investigation of interlinkages, highlighting the indicators that influence the most the remaining metrics.

In the MICMAC analysis, a graph classifying the indicators based on the driving and dependence powers is developed. Therefore, the indicators are clustered into the following four groups:

Group I – Autonomous Indicators that have weak driving and dependence power, indicating a relevant disconnection from the system.

Group II – Dependent Indicators that have weak driving power but strong dependence power, indicating that these indicators are strongly affected by other indicators but they have weak influence on others.

Group III – Linkage Indicators that have strong driving and dependence power, indicating their instability as they connect different indicators (meaning that they both are impacted by and impact other indicators) resulting in ripple effects.

Group IV – Independent/Driving Indicators that have strong driving power but weak dependence power, indicating that they are minimally influenced by other indicators but they have a strong impact on indicators thus, requiring maximum attention.

The results of the MICMAC analysis are also presented and discussed in the following sub-chapter (4.4).

4.4 Results and discussion

In this section, the results of the ISM model and MICMAC analysis are presented and discussed, followed by a thorough elaboration on the contributions and limitations of the deployed methodology. The interference between circularity indicators and policies is further discussed in the final sub-section.

4.4.1 ISM model results and discussion

The generated ISM model – illustrated in Figure 4.2 – has six importance levels. Level I – placed at the top of the figure – includes the three economic-related indicators (i.e. I3, I4 and I15), indicating that these indicators do not influence any other indicator of the system. In Level II and III consist of ten indicators in total, eight of which are related to the regeneration of natural environment principle (i.e. I8, I6, I14, I16, I17, I18, I19, I20) and two are related to the design out negative externalities principle (i.e. I1, I13). Level IV includes two design out negative externalities indicators (i.e. I11, I12), while Circular Use (I5) and Circular Flow (I7) – falling under the keep resources in use principle – are classified as Level V indicators. Level VI consists of three indicators, two of which are related to the keep resources in use principle (i.e. I2 and I9) and one (i.e. I10) of the regeneration of natural environment principle.

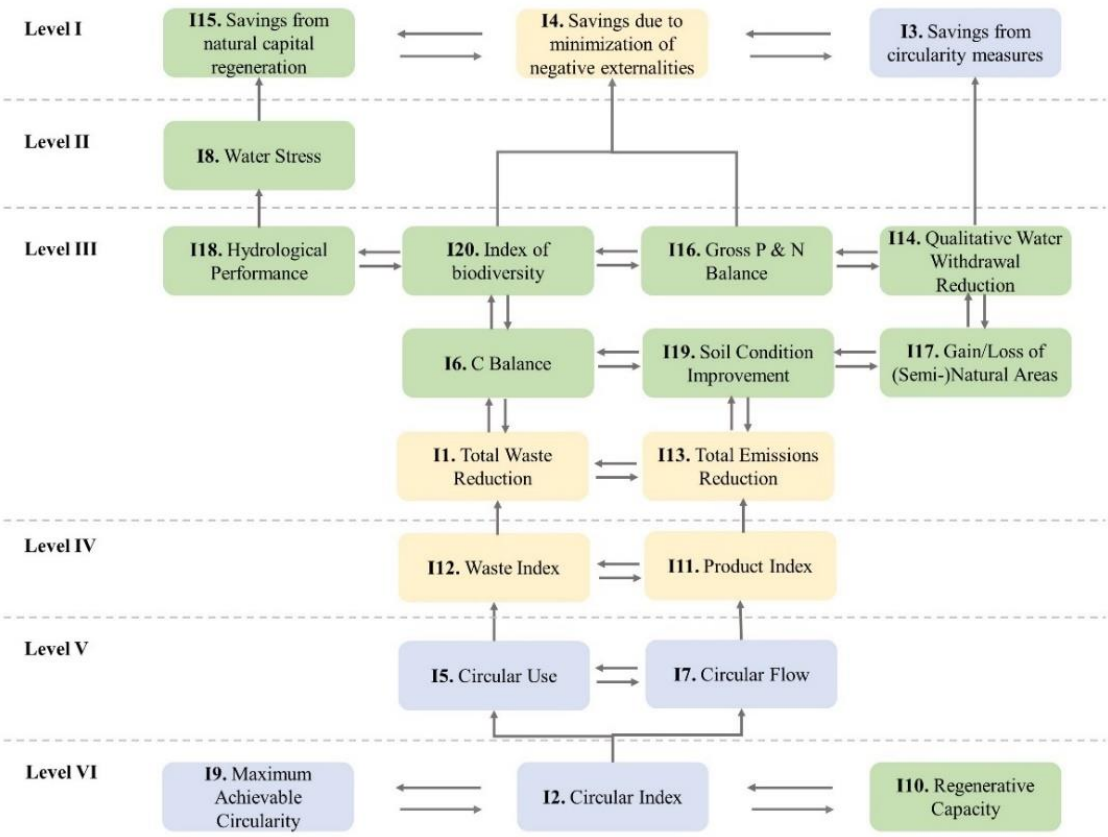


Figure 4.2: The six – level ISM model for interdependent CE indicators

Figure 4.2 indicates that the most critical indicators are the maximum achievable circularity (I9), the circular index (I2) and the regenerative capacity (I10) that are interdependent to each other and these three indicators will affect all the remaining seventeen indicators. Maximum achievable circularity indicates the physical limits of the anthropogenic system to close its loops, while the regenerative capacity represents the limits/thresholds of the natural system that should not be crossed. Circular index cannot overcome the maximum achievable circularity and should remain under the local regenerative capacity and in fact it should focus on even improving it. The results seem to be in line with recent studies indicating the increasingly recognised importance of the Planetary Boundaries concept (Rockström et al., 2009) to CE in order for the latter to remain within a safe operating space (Harris et al., 2020; Kalmykova et al., 2018; Korhonen et al., 2018). Therefore, CE efforts should first and foremost measure and evaluate the local physical and natural limits and how circularity is influenced by or influences them – the correlation between the regenerative capacity of the area, the maximum achievable circularity and the circular index.

4.4.2 MICMAC analysis results and discussion

The position of the indicators in the Driving – Dependence power graph derived from MICMAC analysis is illustrated in Figure 4.3. The indicators are located in Group II, III and IV, indicating that there are no autonomous indicators in the system.

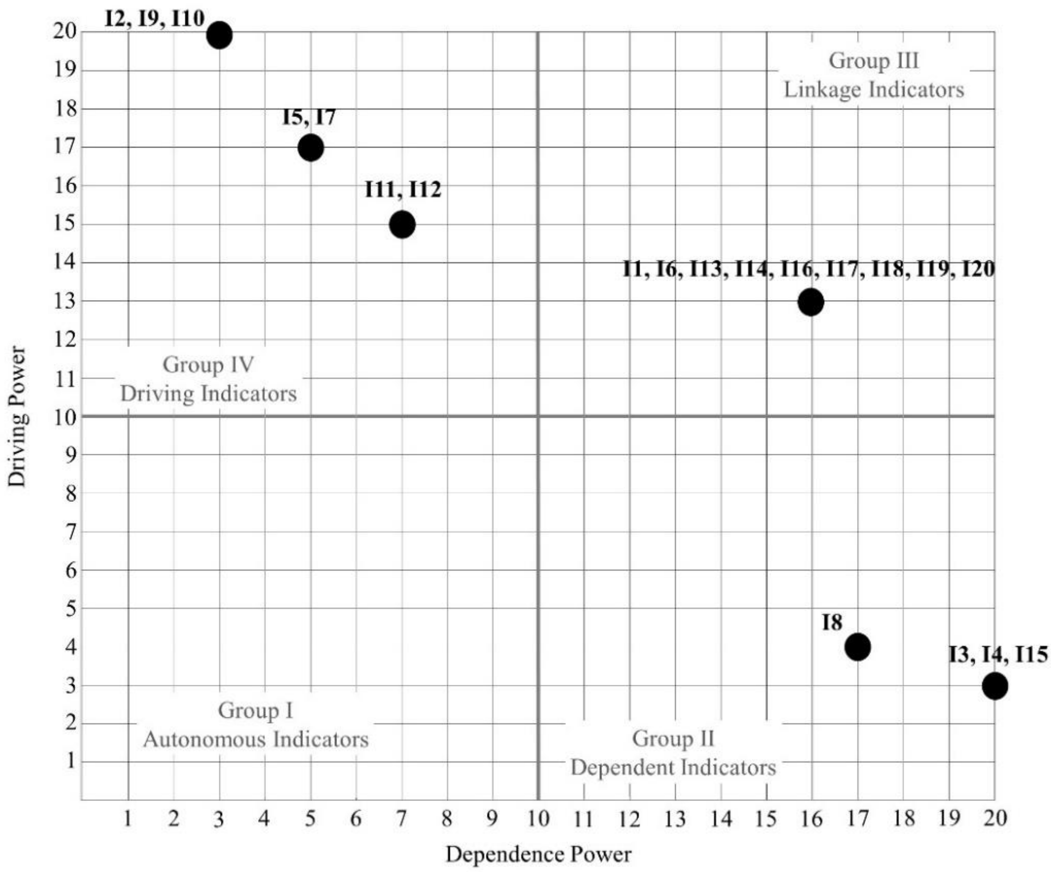


Figure 4.3: MICMAC analysis

In Group IV, there are seven indicators identified as driving indicators, namely circular index (I2), maximum achievable circularity (I9), regenerative capacity index (I10), circular use (I5), circular flow (I7), product index (I11) and waste index (I12). Among these indicators, two (I11, I12) are related to the design out negative externalities principle, four (I2, I5, I7, I9) are related to the keep resources in use principle, and one (I10) is related to the regeneration of natural environment principle. Therefore, it is indicated that the indicators' positioning in Figure 4.3 does not necessarily represent the importance level of the indicators (Figure 4.2). Level IV and V indicators are specified as driving indicators, along with the most important indicators of Group VI, signifying a strong driving power in impacting all other indicators. These seven driving indicators are in fact intrinsic circularity indicators – following the indicators taxonomy proposed by Saidani et al. (2019) – that measure the inherent circularity of a system. The driving indicators are the most important indicators to be measured as they influence all the remaining indicators.

Nine indicators (i.e. I1, I6, I13, I14, I16, I17, I18, I19, I20) are identified as linkage indicators, positioned in Group III. These nine indicators have mutual dependency and their positioning indicates that a change in any of these indicators will result in a ripple effect affecting all the other indicators of this group. Considering the indicators taxonomy of Saidani et al. (2019), these linkage indicators are specified as consequential indicators, measuring the impacts of CE. The linkage indicators are important to be measured and monitored as they indicate the consequences of CE implementation. However, depending on the target system, some linkage indicators can be more important than others. For example, in a system where biodiversity is significantly reduced it would be important to measure and evaluate how and if CE actions affect the index of biodiversity, while in a system where agriculture is the main economic activity and the major system's component the importance of monitoring soil condition improvement increases. Therefore, the selection of indicators strongly depends on the system, with the most important indicators to be regularly monitored and reported while the remaining could be monitored less frequently. That is because these indicators are interrelated indicating that the incorporated ripple effects may result in impacts, which can be neglected if not monitored at all.

In Group II, the remaining four indicators are identified as dependent indicators. These indicators include the three economic-related indicators of savings from circularity measures (I3), savings due to minimization of negative externalities (I4) and savings from natural capital regeneration (I15), as well one indicator targeted at the regeneration of natural environment principle; i.e. water stress (I8). This group includes indicators that strongly depend on the results of the other indicators but they do not influence any of them. Economic-related indicators are high in the hierarchy of the stakeholders ranking (Table 4.1). Although these indicators cannot in-fluence the behaviour of the other ones, they can play an important role towards the transition to CE by providing important incentives to stakeholders. All four indicators are specified as Level I and II indicators in (Figure 4.2).

4.4.3 Contributions, recommendations and limitations

This study develops a framework for CE indicators selection that is based on a computer-assisted learning process, using ISM approach and MICMAC analysis. This approach enables the investigation of interrelationships among various circularity performance indicators for the WEFE nexus and enables the identification of the driving indicators, i.e., the indicators that influence the remaining indicators the most. The interrelationships are represented in a hierarchical manner that classifies the indicators based on the degree of influence, enabling the investigation of the behavioural aspect of indicators. The behaviour of an indicator when it interacts with other indicators is of major importance in order to better understand which indicators would influence the results of a circularity assessment the most by identifying the interlinkages of the indicators system. As observed in the literature, very few studies have applied multi-criteria decision-making treatment for identifying the interrelationships between indicators, while none of them has focused on CE indicators related to the WEFE nexus. This study explicitly examines the relationship among a set of twenty CE indicators targeted at the WEFE nexus that will assist the practitioners and researchers to understand the behaviour of these indicators. All CE indicators cannot be implemented simultaneously. However, if the behavioural aspect and the relationships among these indicators are obtained, practitioners, scholars and policymakers of the nexus will be facilitated.

Focusing on the specific results of this study, the twenty analyzed CPIs were divided into three groups: seven driving CPIs (intrinsic indicators), nine linkage CPIs (consequential indicators), and four dependent CPIs. The results indicate that CE planning and implementation should start from an in-depth analysis of the local context and conditions, including an investigation on the regenerative capacity based on local safe operating spaces, as well as on the local maximum achievable circularity and the required circular index, adequate to perform under the local limits. These results are in line with the increasing recognition of a territorial approach to circularity indicating that CE materializes in very different ways based on the local conditions, needs and risks in which it operates (Alessandrini et al., 2019). While the circular index is simple to measure, the regenerative potential and ultimate achievable circularity are more aspirational measures, and future research should concentrate on developing measurement and evaluation methodologies for these two indicators. Following the specification of these values for the local context, CE calculation and evaluation should begin with a comparison of the adopted measures to these goals. Equally important is the evaluation and reporting of the circular use and flow and the product and waste indices, since these indicators have a significant impact on both consequential and dependent indicators. Monitoring and reporting of consequential or linkage indicators would show the impacts of the intrinsic indicators to both the human-managed (e.g., waste reduction) and nature-managed (e.g., soil condition improvement) systems. These indicators would prove whether or not CE measures work in the right direction and would further affect the economic-related indicators. It is worth noting that these last indicators have been signalized by the consulted stakeholders as highly relevant, and though they have shown not to affect any other indicator of the system, any comprehensive CE assessment should consider the valorization of potential revenues/savings from natural capital regeneration, minimization of negative externalities and circularity measures. To do that, a wide variety of economic methods based on market and non-market approaches are available (Nika et al., 2020b).

Despite the study's significant contributions to the identification of indicators for the WEFE nexus, it has a number of limitations. The study's first drawback is that the contextual relationship of the indicators depends on experts judgement, which may be biased and therefore influence the results. To overcome this drawback, it is suggested to carefully select the experts based on their in-depth knowledge and experience on the specific indicators that are investigated, as well as on the studied system, level of implementation and sector specificities. Additionally, primary emphasis should be placed on saturation (Miles and Huberman, 1994), e.g., the experts can be interviewed multiple times until no new substantive information is obtained. Furthermore, the model has not been statistically checked. To further confirm these results, structural equation modelling (SEM) may be used. Integrating model/equations for estimating values of indicators in addition to experts' assessments will increase the applicability and transferability of the method across case studies. Indicators estimated with SEM approach can be checked by experts and facilitate the validation of the method. The models/equations need to be supported with a concept database structure including publicly available data as well as specific data to case studies, which on one hand can be a bottleneck for applying the method, on the other hand it can be a driver for better organisation of public data sets to be used for estimation of circularity indicators.

Another drawback is that the current model only considers twenty macro-level CPIs that were produced by Nika et al. (2020b) and validated by experts. However, the literature contains several collections of CE macro-level metrics, implying that the CPIs examined are not exhaustive. In fact, appropriate indicators for monitoring and assessing CE are case-specific, depending on the sectors, supply and value chains, processes, products, resources and materials involved in the investigated system, indicating that CE indicators at various implementation levels (e.g., micro, meso) or sector-specific indicators can yield different results. Therefore, this study does not aim at indicating a specific set of CE indicators that are important and appropriate in all cases, but rather proposes a versatile methodology able to identify comprehensive indicators relevant to the specific systems.

4.4.4 Interface with policy, regulation and finance

Sound analytical framework of circularity indicators within the WEFE nexus cross sectoral perspective is crucial in the current conjuncture of ambitious global (e.g. Sustainable Development Goals) and continental (e.g. European Green Deal) water-, energy- and food-related objectives, which securities are inextricably inter-linked and all supported by ecosystems (Bidoglio et al., 2019; Malagó et al., 2021).

Circularity indicators are also fundamental to direct and monitor effectiveness of investments towards sustainable projects and initiatives. In Europe, the recent action plan on financing sustainable growth (EC, 2018b) aims at establishing a clear and detailed EU Taxonomy, a classification system for sustainable activities. However, validated circularity indicators that consider and quantify WEFE inter-sectorial linkages are still missing and are not supporting decisions and framework to facilitate sustainable investments.

The harmonization of water, energy and food policy targets considering the benefit for the natural capital should also guide the currently evolving European water-related legislative and regulatory framework. Besides the EU Green Deal, there is a number of legal files relevant for the water sector under evaluation, revision or approval at EU level. Furthermore, unpredictable events, such as the Coronavirus pandemic, have heavily influenced the policy priorities. In this context, the alignment of new solid CE indicators with EU policies is crucial.

Finally, the CE indicators can support policy integration and wider perspective for the payment and reward of ecosystem services, even for their inclusion in the water and energy tariff framework. At the moment, mainly sectorial mechanism to evaluate the Environmental and Resource Cost (ERC) and reward the ecosystem services are applied, for example to the full recovery cost (FRC) within the water tariff. For instance, in Italy mainly aquatic ecosystems are considered (ARERA, 2020), while indicators considering the WEFE nexus might better represent the needed holistic approach.

4.5 Summary of main findings

The development of performance indicators adequate to holistically and systemically measure circularity receives increasing attention towards a successful transition to CE. Yet, there is not a single widely accepted set of CE indicators. The indicators selection process is a key step for a holistic and sufficient evaluation of CE actions, requiring the consideration of multiple circularity aspects, systems specificities, scientific knowledge and practical needs of related stakeholders. In cases where system’s value chain exceeds the sectoral boundaries and nexus approaches are required, the complexity of measuring and assessing circularity increases significantly influencing the selection of appropriate CE indicators. It is therefore important to consider the behavioural aspect of CE indicators in order to better understand the interdependencies between them, facilitating the indicators selection procedure based on solid justification.

The current study focused on a set of macro-level CE indicators for the WEFE nexus, validated by academic and industrial experts in the field. The validated indicators were analysed using ISM modelling and MICMAC analysis in order to identify direct and indirect relationships between these indicators. Six importance levels were identified in the ISM model, indicating that the most critical indicators – based on the structural hierarchy – are the maximum achievable circularity, the circular index and the regenerative capacity. The MICMAC analysis resulted in seven driving, nine linkage and four dependent indicators. The MICMAC analysis results provide additional insights regarding the indicators interconnections. Based on these results, the seven driving indicators – consisting of two design out negative externalities indicators and four keep resources in use indicators – are the ones that will influence the results of all the remaining indicators. According to the findings, regenerative capacity, overall achievable circularity, and the circular index are among the most important driving measures of circularity, followed by circular usage and flow, commodity and waste indices, and so on. These indicators should be at the heart of a CE assessment protocol that contributes to the achievement of consequential and economic-related goals.

The results of this study will help researchers, practitioners, and policymakers prepare and execute CE strategically, as well as define and use relevant metrics to assess and evaluate CE in a systematic way. As future research, Structural Equation Modelling (SEM) can be integrated in the proposed methodology to additionally formalize the cause and effect relationships between indicators. The latter would provide statistical checks of the method, more independency from experts' opinions and facilitate transferability to different case studies including validation of the method itself.

5. Assessing circularity of multi-sectoral systems under the Water-Energy-Food-Ecosystems (WEFE) nexus

5.1 Introduction

As defined by Ellen MacArthur Foundation (EMF, 2017a), the Circular Economy (CE) recognizes systems thinking by considering the three dimensions of sustainability as a prerequisite for the transition towards a regenerative economic development, decoupled from the consumption of finite resources. However, two recent studies (Kirchherr et al., 2017; Friant et al., 2020) revealed the existence of more than 110 definitions of CE (i.e. 114 and 120 definitions, respectively). Different definitions inevitably result in different CE principles, goals and objectives.

Circularity measurement entails the development of CE metrics/indicators that measure and evaluate the progress of CE actions in a specific system (Moraga et al., 2019). Different circularity goals resulted from different CE definitions compounds the assessment of CE. Adding to the complexity of the topic, measuring circularity further requires the consideration of system/sector/nexus specificities (EC, 2020), appropriate implementation and assessment levels (Saidani et al., 2017), as well as the incorporation of multiple aspects/capitals (Yorkshire Water, 2021). Although an extensive amount of CE indicators exists in the literature (see e.g. Helander et al., 2019; Moraga et al., 2019), many reviewers have concluded that existing indicators fail to holistically and systemically measure CE, which may lead to the undesirable self-selection of indicators by organizations (Pauliuk, 2018).

In the water sector, which is mandated to be approached from a nexus perspective according to the new CE Action Plan (EC, 2020), few studies have focused on the identification, selection and/or application of CE indicators. Kayal et al. (2019) proposed the Wastewater Circonomics Index as a CE metric that measures production, recycling and reuse efficiencies of Wastewater Treatment Plants (WWTPs) under monetary terms. Ghafourian et al. (2021) conducted a literature review on economic assessment methods and indicators that can be used to estimate the economic, environmental and social costs and benefits of Nature-based Solutions (NBS) as enablers of circularity in water systems. Both studies focus on the economic aspect of CE that is an important element of assessment methodologies. Valencia et al. (2022) developed a methodology combining a system dynamics model, multicriteria decision-making and cost-benefit-risk trade-off analysis to investigate the circularity potential of the Food-Energy-Water-Waste nexus in Orlando, Florida under different scenarios. The analysis, assessment and selection of the optimal option was based on specific indicators. Nika et al. (2020b) developed the Multi-Sectoral Water Circularity Assessment (MSWCA) framework that assesses circularity of complex systems under the Water-Energy-Food-Ecosystems (WEFE) nexus and proposed a thorough list of indicators that can be applied in various systems. The MSWCA includes indicators that are able to cover all the socio-economic and non-economic sectors of the nexus, their incorporated resources, the three CE principles and additional economic, environmental and social aspects. Later on, Nika et al. (2021) suggested a dynamic indicators' selection process based on stakeholders' participation and application of the Interpretive Structural Model that enabled the provision of information regarding the influence and the interrelationships between indicators. This approach lies on its reliance on experts' opinion.

The current study aims to develop consensus on the behaviour of CE indicators under the WEFE nexus by applying the MSWCA framework to an actual case study developed within the HYDROUSA H2020 project. Following the MSWCA framework, a systematic approach for the indicators selection process is being developed to holistically measure circularity of a system, considering the following aspects: lifecycle stages; mono-functionality of linear systems versus multi-functionality of circular; additional environmental, economic, and social benefits and costs; water, energy, resources, waste and emissions, economic and other indicator-related categories; the three CE principles. The present study focuses on the validation of the selected indicators based on their sensitivity to capture changes that may occur in the system. Different scenarios are tested to investigate how indicators changes would affect the circularity performance of the investigated system. The indicators are further related to the SDGs to evaluate their potential to address sustainability.

5.2 Methodology

5.2.1 Description of the HYDROUSA case study

The system under investigation – thereafter HYDRO system – is implemented in the HYDROUSA Horizon2020 Innovation Action project (Grant Agreement No 776643) and located on the Greek island of Lesvos in North-Eastern Aegean Sea. The HYDRO system combines grey infrastructure with NBS and consists of a sewage treatment system (HYDRO1) that is implemented on an existing WWTP, treating the domestic wastewater of Antissa village, and of a new agroforestry system (HYDRO2) – considered as an NBS – located at the surroundings of HYDRO1. HYDRO1 combines anaerobic processes (Uplflow Anaerobic Sludge Blanket – UASB reactor) with saturated and unsaturated vertical flow constructed wetlands (CW) – considered as an NBS – and disinfection, combined with ultrafiltration (UF) and UV systems to treat domestic wastewater. The produced sludge is further treated in a compost unit while the biogas produced in the anaerobic process is also recovered and the produced energy is used to cover part of the system's energy needs. HYDRO2 covers an area of 1 ha that includes forestry trees for fruit and timber production, orchards/bushes, herbs and annual crops. HYDRO2 is fertigated in the summer period using the reclaimed water from HYDRO1, while the produced compost is applied to HYDRO2 once per year. Local producers will collect the yielded crops and fruits in return for payment and they will sell the products in the local market. The self-collection of crops is expected to increase the farmers' awareness of agroforestry systems, sustainable agriculture and circular solutions. A visual representation of the investigated HYDRO system – indicating the symbiosis between WWTPs and agriculture under the CE – as well as the resource flows of the system can be seen in Figure 5.1 (a) and (b).

5.2.2 Implementation of the MSWCA framework to assess circularity of the HYDRO system

The MSWCA (Nika et al., 2020b) is a versatile methodological framework that provides guidelines for holistically and systemically assessing circularity of multi-sectoral systems under the WEFE nexus. The investigation of interdependencies and feedback loops between the different system components lie at the core of the MSWCA framework therefore, careful selection of indicators in order to capture changes that may occur in the system is of major importance.

In this study, the five distinctive methodological phases of the MSWCA – i.e. system development, system synthesis, system analysis and assessment, system testing, and system prediction and attainability – are applied in the HYDRO system. Each of them is analysed in the following sub-sections in terms of relevant information that should be considered in order to aid a systematic indicators selection process.

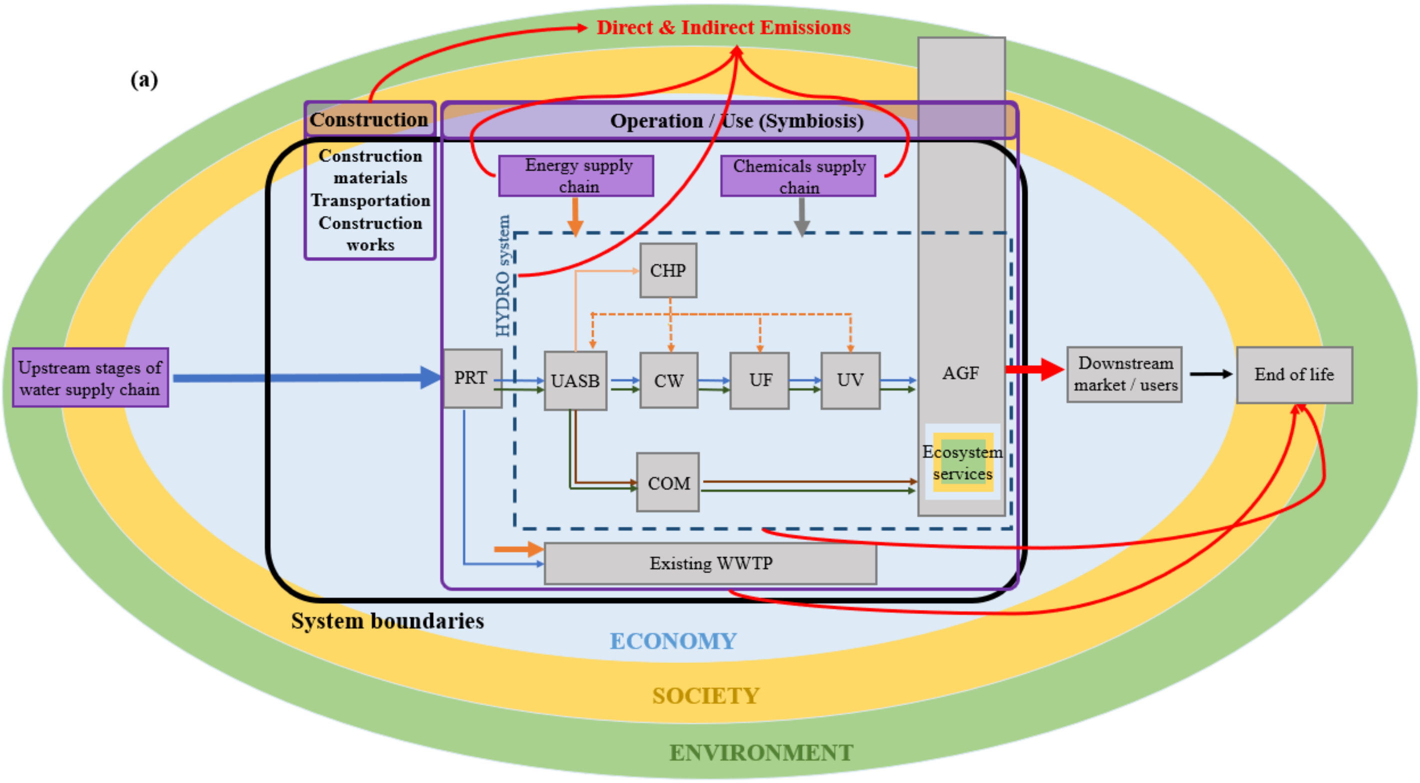
5.2.2.1 System Development

System development phase is a critical step for the indicators selection as it defines the goal and scope of the circularity assessment. This phase entails a clear understanding of the subject of the assessment (e.g. technology, product, company, symbiosis, city, region, nation), and whether or not the implementation scale of circularity actions coincides with the scale of the circularity assessment.

Scope of the assessment: For the investigated HYDRO system, the symbiosis between a WWTP and a farming system is the subject of the assessment, i.e. how the interaction between HYDRO1 and HYDRO2 would affect circularity performance of the entire system.

System's functionality: The system's functionality is a key aspect for two main reasons: 1) a system (either technical, economic, or ecological) that does not fulfil its main functionality will not be able to survive, as it is mathematically described by Marti (2008), and 2) comparison can only be made between systems that share the same main functionality (e.g. WWTPs cannot be compared with computer manufacturing companies). The principal objective of a WWTP is to treat wastewater so that the effluent can be discharged to the environment without danger to human health or unacceptable damage to the natural environment. The main function of a farming system is to produce food and other crops in order to meet the nutritional needs of the consumers and the financial needs of the producers. Another important aspect that normally differentiates a circular from a linear system and which is rarely being discussed is that circular systems tend to have multiple functionalities compared to mono-functional linear systems (Brown, 2018; Ingemarsdotter, 2021). For example, energy systems are designed to produce energy, or WWTPs are designed to treat wastewater, but designing a WWTP to become more circular often incorporates the simultaneous production of energy, recovery of different resources/materials, and treatment of the received wastewater. Multifunctionality can be achieved by two means, i.e. either combining multiple mono-functional components or one multi-functional component (e.g. NBS) (Nika et al., 2020a). In the HYDRO system, additional functionalities include water reuse, bio-fertilizers production and reuse, and renewable energy production and reuse, as well as multiple benefits obtained from agroforestry, such as increased biodiversity, improved soil structure and health, reduced erosion, and carbon sequestration. System's multi-functionality needs to be considered in the assessment and depicted with the selected indicators.

Boundaries definition: In this case, the implementation and assessment scale are the same. The assessment boundaries could be expanded if for example, the purpose was to assess the interaction between the HYDRO system and the broader WEFE nexus of the region. The interaction between HYDRO1 and HYDRO2 is evaluated in the operation/use or symbiosis phase. This phase includes the evaluation of all inputs and outputs of the system, the exchange of resource, material, product flows between the different system components and the incorporated indirect supply chains (i.e. energy and chemicals supply chains). The construction phase of the HYDRO system is also considered in the assessment. The system boundaries and resource flows for the HYDRO system are illustrated in Figure 5.1.



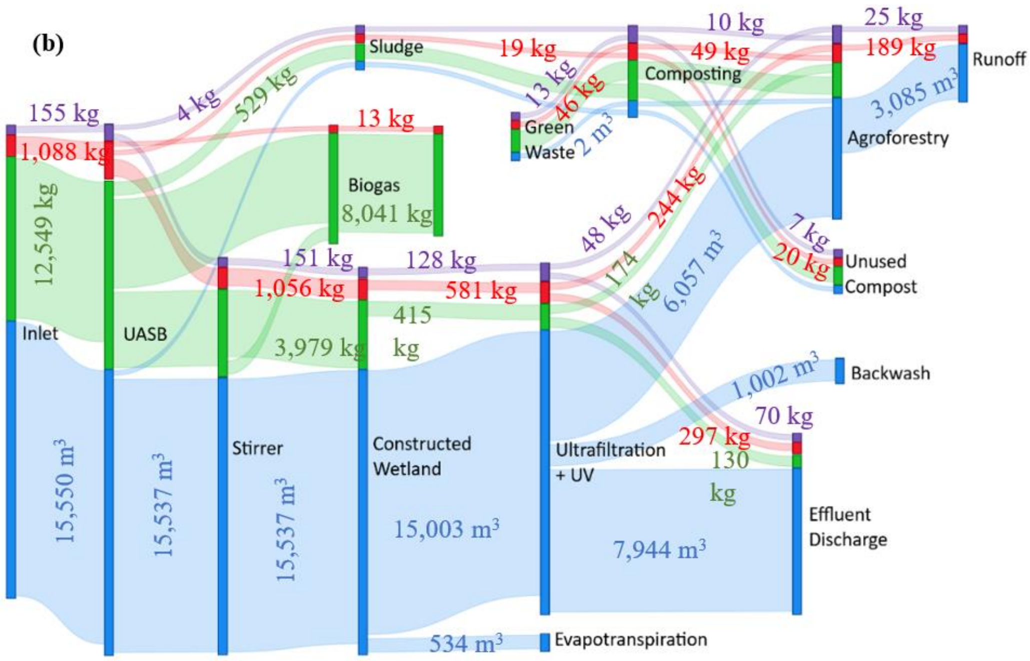


Figure 5.1: System boundaries of the HYDRO system (a) and Sankey diagram of HYDRO system (b), in which, water is illustrated in blue, COD in green, nitrogen in red, and phosphorus in purple

As shown in Figure 5.1, the agroforestry further interacts with the broader natural environment but investigation of such interactions is out of the scope of this study. Downstream market, users and the impacts of the end of life phase are out of the scope of the study as well. In the current work, all the products are considered as system outputs that are either being used (e.g. the produced food) or discharged/disposed (e.g. the remaining treated wastewater and compost). Circularity conceptualization: In order for a system to be characterized as circular, its multi-functionality needs to be fulfilled through the achievement of the three CE principles. In the investigated HYDRO system, the main function of effectively treating wastewater falls under the principle of "Design out negative externalities". Food production is expected to be achieved through the realization of "Keep resources, materials and products in use" principle – in terms of water, energy, carbon, phosphorus and nitrogen flows – and through the realization of "Regeneration of Natural Capital and Environment" principle. The latter principle is differentiated between local regeneration and regional or global regeneration. Local regeneration focuses on the provided ecosystem services, biodiversity increase, and land use change, while regional/global regeneration targets at the avoided resources (i.e. fresh water, fertilizers, non-renewable energy) that would be required to operate the system if circularity actions were not taken. Additional benefits and costs of the HYDRO system are evaluated based on the additional materials that are used, including bio-materials (such as green waste required for the compost unit) and chemicals required for the operation of the CHP unit, as well as the UF. Negative environmental impacts of the HYDRO system are differentiated between primary impacts related to the local environment (i.e. direct and actual emissions and remaining waste) and secondary impacts related to regional or global potential impacts arising from the considered life-cycle stages and the indirect supply chains of the system (i.e. direct and indirect emissions). Economic impacts are evaluated based on the revenues and savings arising mainly from the "Keep resources, materials and products in use" principle, while social impacts are considered through the cultural ecosystem services provided through the "Regeneration of Natural Capital and Environment" principle.

5.2.2.2 System Synthesis

System synthesis phase develops the model that is used for the assessment considering the system boundaries, the focus of the assessment, as well as the defined multi-functionality and the aspects that fall under the three CE principles. The developed model results in a static or dynamic assessment, or a combination of both. Static (benchmark) assessment uses data and/or models to evaluate the system and compare it with the baseline scenario or any change / intervention planned. Dynamic assessment is related more with the assessment of the system for optimization using continuous monitoring data and dynamic modelling procedures.

The HYDRO system's construction phase uses data regarding the amount of materials and resources (e.g. water and energy) used to construct the system, the transportation of materials to the HYDRO system, construction work conducted on site, changes in land use land cover and incorporated costs to build the system. The construction phase does not affect the symbiosis between HYDRO1 and HYDRO2 but the embodied environmental impacts (estimated using LCA); circularity-related indicators, and capital expenditure (CAPEX) need to be considered in the final assessment.

The HYDRO system's operation/use is the phase that affects the symbiosis between HYDRO1 and HYDRO2 and therefore, requires a dynamic assessment to support process optimization. The HYDRO system consists of an anthropogenic sub-system (i.e. HYDRO1) and a nature-managed sub-system (i.e. HYDRO2). Starting from the anthropogenic component, HYDRO1 is responsible for treating wastewater and turning it into fertigation water, for producing compost and energy. It is also responsible for energy and chemicals consumption, as well as emissions and waste generation. The treatment, production and consumption of resources, as well as the produced emissions and waste are simulated in the model using mathematical equations (Appendix Modelling Description of System Components) to describe each of the incorporated processes of HYDRO1.

Regarding the nature-managed component, simulation gets more complicated if all the natural processes are to be mathematically described. Both slow and fast natural processes are complex and synergetic and their modelling requires a combination of observation and sampling data and complex simulation models (Ward et al., 2019). In order to avoid overcomplication of the developed model, critical points of intersection between the anthropogenic and nature-managed components have been identified. The latter considers the symbiosis between the two components and the capability of the selected indicators to capture system's changes. A differentiation between HYDRO2 processes that would drive a direct impact and processes that impact less on the symbiosis of the HYDRO system is made. HYDRO2 as a diversified farming system requires water and nutrients of sufficient quantity and quality from HYDRO1 in order to meet its fertigation needs (i.e. main node of intersection). Water requirements of HYDRO2 depend on the species that are planted, local climatic conditions and the used irrigation system. These processes are mathematically described in the model (Eq. C.1-C.6 in Appendix Modelling Description of System Components). Nutrient requirements of plants depend on plants species and soil fertility (Doula and Sarris, 2016). Soil fertility and therefore, vegetation productivity is impacted by numerous interconnected factors, such as microbial activity, nutrients cycling, edaphic conditions, hydrological cycle (Jouquet et al., 2006). In the developed model, nutrient requirements are considered stable and obtained from a preliminary assessment conducted from the local agronomists. Both water and nutrient requirements may further change due to natural processes that will evolve in HYDRO2 (e.g. changes in microbial biodiversity would impact soil fertility, which may change external nutrient requirements or species biodiversity may change the water retention capacity, which may impact the water requirements). Such changes would create natural feedback loops that would further impact the symbiosis between HYDRO1 and HYDRO2. Since the processes that may drive such changes are more complicated and may take years to evolve, the effect of such feedback loops is not considered. Future work can focus on the investigation of the impacts of feedback loops to the system. Therefore, additional benefits of the agroforestry are considered as system's outputs; they qualitatively evaluated using the Ecosystem Services Assessment methodology applied by Everard and Waters (2013) that considers the 'likelihood of impact' scoring system as proposed by Defra (2007). Using this approach, qualitative symbols – from "++" for potential significant positive effect to "– –" for potential significant negative effect – are assigned to all ecosystem services based on experts' opinion (i.e. local agronomists). Additional modelling outputs that are considered include water losses due to irrigation systems used (simulated output), nutrient losses (assumptions based on the nutrient requirements of the species) and food/crop yields based on theoretical literature data that are further validated by the local agronomists and assigned market values of those yields.

Concerning the temporal variation of the model, the anthropogenic model is developed using a daily simulation time step, while the nature-managed model uses a monthly simulation time step. Aggregation is performed at both seasonal and annual levels to enable the integration of anthropogenic and nature-managed models. Seasonal aggregation is considered important in this case, since fertigation of the agroforestry takes place during the summer period only (i.e. beginning of April until the end of September). Daily inputs to the anthropogenic model are considered stable at a seasonal basis (e.g. the wastewater inflow during the summer is constant at 80 m3 per day and 30 m3 per day for the winter period, the UASB temperature is considered constant at 15^{o}C during the winter and 20^{o}C during the summer days, etc.).

The integrated model further includes mathematical descriptions of the selected indicators (presented in Section 5.2.2.3) to estimate the circularity performance of the system. The modelling results of the circularity assessment are reported on a yearly basis (Figure C.1). Input data are inserted in the form of ranges in consultation with the technology experts and literature data to depict potential operation conditions. The model investigates whether the different operational conditions and scenarios would be captured by the selected indicators, and how these changes would affect the circularity performance of the HYDRO system. Input data and data ranges that are used in the model can be found in Table C.1 and Table C.2.

5.2.2.3 System Analysis and Assessment

A systematic indicators selection process is developed as illustrated in Figure 5.2.

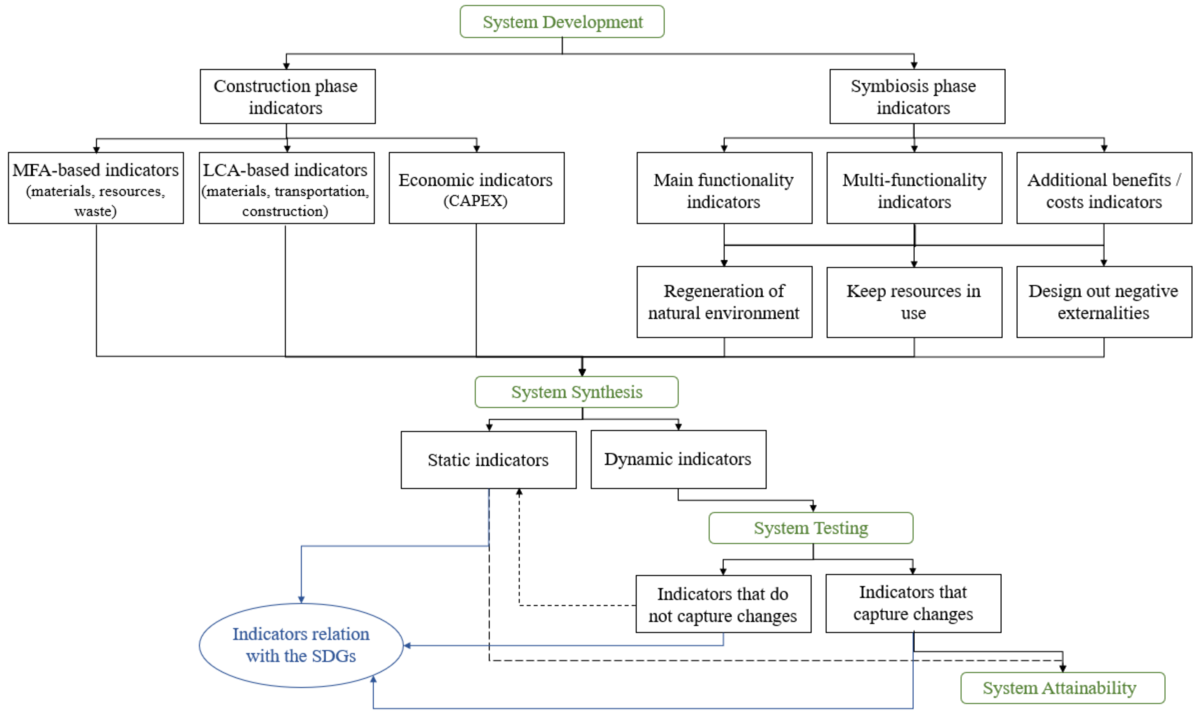


Figure 5.2: Indicators selection process

A list of indicators has been selected (Table 1) for the HYDRO system considering both the construction and symbiotic phases, the multi-functionality and the additional benefits and costs, the three CE principles (as explained in section 2.2.1) and the static (benchmark) and dynamic assessment (as explained in section 2.2.2). Mathematical description and units of all the selected indicators can be found in Appendix Selected Indicators.

Table 5.1: List of selected indicators and categorization based on the analysed criteria. Green colour represents the indicators falling under the Regeneration of natural environment principle, Blue colour represents the indicators under the Keep resources in use, and yellow colour represents the Design out negative externalities principle; Text font: Static indicators, *Dynamic indicators*

	Construction phase			Operation / Use phase		
Category	Built Materials	Transportation	Construction Works	Main Functionality	Additional Functionalities	Additional Benefits / Costs
Resources	Non-renewable materials intensity (NRNMI)				*Produced food per m^3 of treated WW (PF_{fu})*	*Circular Carbon Inflow / Outflow / Flow (CCI / CCO / CCF)*[1]
	Renewable materials intensity (RNMI)				*Produced compost per m^3 of treated WW (PC_{fu})*	*Circular Nitrogen Inflow / Outflow / Flow (CNI / CNO / CNF)* [1]
	New materials intensity (NMI)				*Extended life of C (ELC)*[1]	*Circular Phosphorus Inflow / Outflow / Flow (CPI / CPO / CPF)* [1]

	Recycled materials intensity (RMI)				Extended life of N (ELN)[1]	Circular Organic Materials Flow (COMF)[1]
	Reused / Repurposed materials (RUMI)				Extended life of P (ELP)[1]	Circular Chemicals Flow (CChF)[1]
						Chemicals use intensity per m^3 of treated WW (ChI_{fu})
Water	Water from the mains ($Water_{con.}$)			Irrigation water per m^3 of treated WW (PIW_{fu})	Water Withdrawal Reduction (WWR)	Circular Water Inflow / Outflow / Flow (CWI / CWO / CWF)[1]
	Alternative water source ($Water_{uncon.}$)				Extended life of water (ELW)[1]	Water Demand Minimization (WDM)[2]
					Discharged WW per m^3 of treated WW (DW_{fu})	System's efficiency for operation (SWE)
					Water Withdrawal Reduction per m^3 of treated WW (WWR_{fu})	Natural hydrological performance (NHP)[3]
Energy	Non-renewable energy sources				Energy production per m^3 of treated WW (PE_{fu})	Renewable energy contribution (REC)
	Renewable energy sources				Energy self-sufficiency (ESS)[4]	Energy demand minimization (EDM)[2]
						Energy production efficiency (EPE)
Waste and Emissions	Remaining waste ($Waste_{rem.}$)				Waste Utilization Index (WUI)	Waste Eco-efficiency Index (WEI)[5]
	Utilized waste ($Waste_{util.}$)				Emission Utilization Index (EUI)	Emission Eco-efficiency Index (EEI)[5]
	CF_M	CF_T	CF_{CW}			CF of operation
	CF_{RM}					CF of operation per m^3 of treated WW
Economic	CAPEX				Intrinsic Circularity Revenues (ICR)	Intrinsic Circularity Savings (ICS)
	Yearly CAPEX				Total Revenues (TR)	Lost Revenues (LR)
					Payback Period from circularity (PP)	
					Intrinsic Circularity Revenues per m^3 of treated WW (ICR_{fu})	
Other	System's Land Use				Simpson's Index of Diversity (plant species)	Regulatory ES
	Soil sealing (SS)				Provisioning ES	Supporting ES
	Green land recycling[6] (GNLR)				Cultural ES	
	Grey land recycling[6] (GRLR)					
	Land Densification[6] (LD)					

[1]modified based on WBCSD, 2021 and Enel S.p.A., 2018; [2]modified based on Agudelo-Vera et al., 2012; [3]modified based on Renouf et al., 2017; [4]modified based on Leusbrock et al., 2015; [5]modified based on Villarroel-Walker et al., 2009; [6]modified based on EEA, 2018

The selected indicators of Table 5.1 are differentiated into resource inflows/outflows, waste and emissions, water, energy, economic and other categories to enable the consideration of both systemic (circular) flow measurements and sustainability impacts. Systemic flow measurements include physical measurements of resource inflows and outflows (e.g. CWI, CWO, CWF), retaining/regenerating resource flows inside the system boundaries (e.g. NHP, ESS), as well as maintaining, regenerating and creating resource value (e.g. ELW, PF_{fu}, WUI, EUI, REC). Sustainability impacts cover social (e.g. Cultural ES), environmental (e.g. CF, biodiversity, WWR) and economic (e.g. ICR, ICS, TR) impacts.

To further investigate whether or not the selected indicators of Table 5.1 successfully cover different sustainability aspects, their relation to the 17 SDGs is identified. For this purpose, the indicators are compared to the 17 SDGs using the LinkedSDG (UN, 2020). LinkedSDG is an online tool that automatically identifies keywords related to sustainable development from documents and connects them to the most relevant SDGs and targets (UN, 2020), resulting in a visualization of the targeted SDGs and incorporated targets. Table 5.1 is used as input document to the online tool with some minor modifications, i.e. abbreviations were avoided – e.g. CF was replaced with Carbon Footprint as an indicator for climate change – and the ecosystem services indicators were included in full detail (as presented in Table 2). Using LinkedSDG has the advantage of being a non-subjective and repeatable method for coupling indicators with SDGs and targets and it further allows comparison with other sets of indicators in terms of represented SDGs. The results of the LinkedSDG tool are presented in Section 5.4.

5.2.2.4 System Testing

In this phase sensitivity analysis is performed to investigate the effectiveness of the selected dynamic indicators to capture operational changes in the system and thus, to identify the main operational parameters that affect the system's performance.

The variance-based global sensitivity analysis is selected to gain insight into the robustness of the metric results. A first-order Sobol' sensitivity analysis is applied which provides estimations of both first order (i.e. main sensitivity indices) and total sensitivity indices (Sobol′, 2001). The main effect sensitivity index assesses the individual effect of each input variable to the output variance, considering the variation of the variable but without considering interactions with other variables. The total effect sensitivity index considers the total contribution of each input variable to the output, including the interactions between all input variables. The sampling of the input variables is performed using the Saltelli scheme (Saltelli, 2002; Saltelli et al., 2010). The size was set at $n_0 = 1000$ for each input variable and the total variables investigated were equal to 166; this resulted into approximately 166,000 simulations for each indicator. The analysis is performed using the SALib Python library (Herman and Usher, 2017). It is assumed that the input variables are uniformly distributed. All the investigated variables and their ranges can be found in Appendix Input Data

The results of the sensitivity analysis serve a triple purpose in this study. First, they show which indicators are the most sensitive to operational changes. Second, they further indicate which variables are the most influential (i.e. the variables that affect the indicator results the most). Third, the most influential variables will be subject to change in the system attainability phase (Section 5.2.2.5) in order to compare the system's circularity performance in different operational scenarios.

5.2.2.5 System Attainability

Based on the results of the sensitivity analysis, different scenarios are selected to investigate potential changes in the circularity performance of the system (results presented in Section 5.3.3). The first scenario uses the design values of the input parameters (i.e. baseline scenario). The other investigated scenarios use the minimum and maximum values of the parameters that affect the system the most; these are decided based on the results of the sensitivity analysis.

The results of this phase indicate under which scenario the system obtains a better circularity performance. System attainability results can be therefore used to advise the relevant stakeholders on how to better operate their system and to inform them on the expected circularity impacts that would occur based on both their decisions and unavoidable changes.

5.3 Results and Discussion

5.3.1 Benchmark Assessment

The benchmark assessment results, comparing the circularity performance of the baseline scenario (i.e. the existing WWTP before its upgrade to the HYDRO system) and Scenario 0 (i.e. after the implementation of the HYDRO system), are presented in Table 5.2. The indicators related to the construction phase of the system are expressed as the ratio of the actual value to the functional unit of the construction phase (i.e. the total area occupied by the HYDRO system). Since the construction phase indicators for the baseline scenario could not be estimated due to a lack of relevant data, these indicator results are not analysed. However, the results presented for Scenario 0 can be used as a reference for future comparison with other similar systems that are newly built. In the operation phase, the indicators related to the main and additional system's functionalities, as well as 8 indicators (i.e. CWF, NHP, REC, CCF, CPF, CF_{fu} and consumed energy per functional unit – CE_{fu}) representing additional benefits and costs of the system are considered for the comparison. Only the PP indicator – targeting additional system's functionalities – is excluded because it could not be estimated for the baseline scenario. Table 5.2 further includes the expected result of each ES category expressed in qualitative terms.

Table 5.2: Benchmark assessment results for the baseline scenario and the HYDRO system

Construction phase			
Indicator Category	**Indicator**	**Baseline Scenario (existing WWTP)**	**Scenario 0 (HYDRO system)**
Resources	NRNMI [kg/m^2 of land]	N.A.	171.95
	RNMI [kg/m^2 of land]	N.A.	0.01
	NMI [kg/m^2 of land]	N.A.	171.51
	RMI [kg/m^2 of land]	N.A.	0
	RUMI [kg/m^2 of land]	N.A.	0.44
Water	$Water_{con.}$ [m^3/m^2 of land]	N.A.	0.04
	$Water_{uncon.}$ [m^3/m^2 of land]	N.A.	0
Waste and Emissions	$Waste_{rem.}$ [kg/m^2 of land]	N.A.	4.70
	$Waste_{util.}$ [kg/m^2 of land]	N.A.	0
	CF_M [kg of CO_2 eq./m^2 of land]	N.A.	11.79
	CF_T [kg of CO_2 eq./m^2 of land]	N.A.	2.94
	CF_{CW} [kg of CO_2 eq./m^2 of land]	N.A.	1.31
	CF_{RM} [kg of CO_2 eq./m^2 of land]	N.A.	0.01
	CF_E [kg of CO_2 eq./m^2 of land]	N.A.	16.04
Economic	CAPEX [€/m^2 of land]	N.A.	50.85
	$CAPEX_{annual}$ [€/m^2 of land per year]	N.A.	2.96
Other	SS [m^2/m^2 of land]	N.A.	0.03

	GNLR [m^2/m^2 of land]	N.A.	0.97
	GRLR [m^2/m^2 of land]	N.A.	0.03
	LD [m^2/m^2 of land]	N.A.	0.11
	Operation phase		
Water	CWF	0.00	0.75
	WWR	-1.00	0.59
	NHP	9.00	0.55
	ELW	1.00	1.30
Energy	REC	0.00	0.23
	ESS	0.00	0.23
Resources	CCF	0.00	0.77
	ELC	1.00	1.63
	CNF	0.00	0.80
	ELN	1.00	1.27
	CPF	0.00	0.76
	ELP	1.00	1.37
Waste & Emissions	WUI	0.00	0.34
	EUI	0.00	0.54
Biodiversity	Biodiversity	0.00	0.74
Economic	ICR [€]	0.00	56,857
Technical	PF_{fu} [kg/m^3 of treated WW]	0.00	0.57
	PC_{fu} [kg per m^3 of treated WW]	0.00	0.18
	PE_{fu} [kWh/m^3 of treated WW]	0.00	1.79
	CE_{fu} [kWh/m^3 of treated WW]	3.59	5.90
	PWI_{fu} [m^3/m^3 of treated WW]	0.00	0.39
	DW_{fu} [m^3/m^3 of treated WW]	1.00	0.58
	WWR_{fu} [m^3/m^3 of treated WW]	-1.00	0.82
	CF_{fu} [kg CO_2 eq./m^3 of treated	8.28	7.97
	TR_{fu} [€/m^3 of WW treated]	2.50	6.16
Provisioning ES	Fresh water Food Fibre & Fuel Genetic resources Biochemicals Ornamental resources	– –	++
Regulatory ES	Air quality regulation Climate regulation Water regulation Natural hazard regulation Pest regulation Disease regulation Erosion regulation Water purification Pollination	– –	++
Supporting ES	Soil formation Primary production Nutrient cycling Water recycling Photosynthesis Provision of habitat	– –	++
Cultural ES	Cultural heritage Recreation & tourism Aesthetic value Spiritual & religious value Education resources Social relationships	– –	+

The results of the operation phase presented in Table 5.2 indicate that the implementation of the HYDRO system significantly improves the circularity performance of the existing system. In the baseline scenario the treated wastewater is discharged to the sea, resulting in both linear resource flows and lost resource values as indicated by the values of 14 indicators (i.e. CWF, WWR, ELW, REC, ESS, CCF, ELC, CNF, ELN, CPF, ELP, WUI, EUI and ICR). As it is expected, no additional functionalities are provided by the baseline scenario, including the lack of ES provision. On the other hand, in the HYDRO system, the experts consulted for the qualitative evaluation expect that the system will have a positive contribution to all ES categories. The HYDRO system would provide food, genetic resources, natural medicines and ornamental resources. It would also have a positive impact to the air quality regulation, enhance soil formation further contributing to carbon sequestration, erosion regulation and nutrients cycling. The enhancement and restoration of the natural water cycle via processes, such as infiltration, recycling of evapotranspiration and runoff reduction is already indicated by the value of the NHP indicator. The utilization of the site for recreation and educational purposes is further expected to have a positive impact to the cultural ES. However, sampling campaigns as well as interviews/surveys to the site visitors are further required to quantify the obtained ES and verify the experts' expectations on the significant contribution of NBS to the regeneration of natural systems.

Although the implementation of HYDRO system indicates a significant contribution to CE, there are 2 indicators that require further attention, i.e. CF_{fu} and CE_{fu}. Regarding the CF indicator, the HYDRO system achieves a slightly better value compared to the baseline scenario. It should be noted that the CF_{fu} value for the HYDRO system includes processes that increase the overall CF of the system and which, are absent in the baseline scenario (e.g. energy consumption in agroforestry). However, if carbon sequestration in agroforestry is considered and subtracted from the CF value, the performance of the HYDRO system related to this indicator would be further improved. Regarding the energy consumption (CE_{fu}) in the baseline scenario and in the HYDRO system, it is evident that the latter consumes more energy. The question arisen here is if it is preferred to consume less energy that is produced by fossil energy sources, or to consume more energy that is produced onsite using renewable energy sources.

5.3.2 *Sensitivity Analysis of Indicators*

Figure 5.3 illustrates the results of the sensitivity analysis in terms of median value, 5th and 95th percentiles of the indicators. Median is the value that separates the higher half from the lower half of the indicator results – i.e. 50% of the indicator results are less than and more than the median value – as obtained from the sensitivity analysis. Accordingly, the 5^{th} and 95^{th} percentiles indicate the indicator values for which, 5% of the indicator result set is below and above that value, respectively.

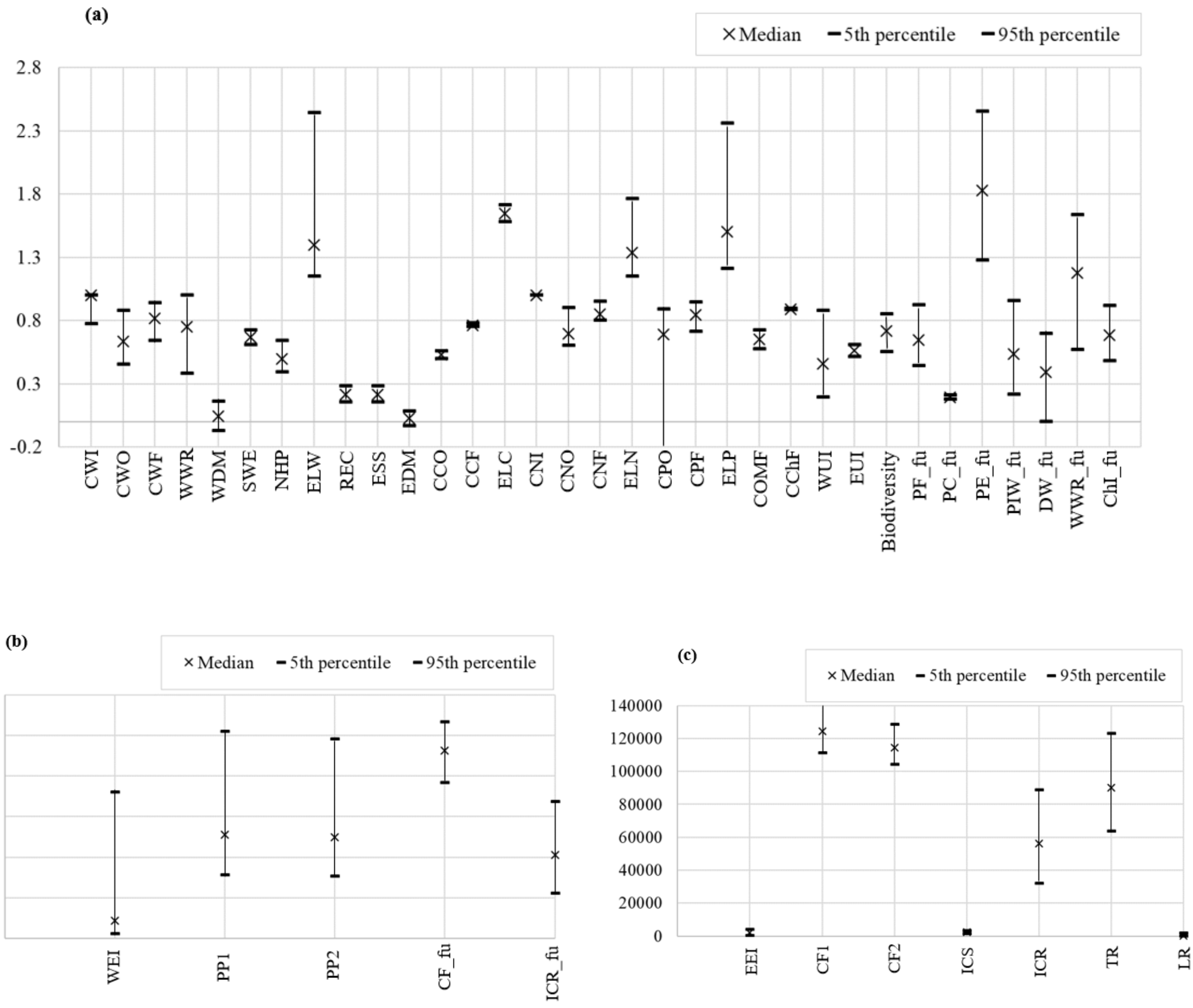


Figure 5.3: Results of the sensitivity analysis showing the median (x), 5^{th} and 95^{th} (-) percentiles of the distribution for all the investigated indicators

The results of the sensitivity analysis in terms of main and total sensitivity indices for all the investigated indicators can be found in Figure C.2 – Figure C.7 (Appendix Sensitivity Analysis Results). Table 5.3 summarizes these results by presenting the most sensitive indicators for each tested variable, considering both the main and total indices. It should be noted that among the 48 selected indicators, 3 (i.e. EPE, CCI and CPI) are identified as static indicators, which means that the value of these indicators remains stable despite changes in the input variables. The five most influential variables that result in the highest main and total indices are identified (in bold font) and are further used for the selection of the investigated scenarios. The definition of the main and total indices is given is Section 5.2.2.3.

Table 5.3: Main and total indices of the indicators that are influenced the most by the investigated variables

Variable	Most Influenced Indicator	Main Indices	Most Influenced Indicator	Total Indices
Influent conc. of TN	CWI	0.04334	CWI	0.23087
UASB COD removal (summer)	ELC	0.33825	ELC	0.39259
CW TN removal (summer)	CNO	0.09652	CWI	0.23819
Influent conc. of P	EUI	0.00218	CPO	0.00088
CW P removal (winter)	ELP	0.05689	ELP	0.07797
CW P removal (summer)	ELP	0.00724	CPO	0.00728
Influent conc. of COD	ChI_{fu}	**0.85575**	REC	**0.80961**
Influent conc. of TSS	-	0	-	0
WW flowrate	EDM	**0.77596**	EDM	**0.78512**
UASB COD removal (winter)	ELC	0.15546	CNI	0.50479
CW COD removal (winter)	CCF	0.00923	CNI	0.23645
CW COD removal (summer)	CWI	0.08482	CNI	0.36945
CW TN removal (winter)	CNI	0.01499	CNI	0.19553
CW green waste	COMF	0.11479	COMF	0.11301
Compost requirements	COMF	0.03908	COMF	0.04181
UF on/off (winter)	WDM	0.06724	WDM	0.10452
UF on/off (summer)	WDM	0.13112	WDM	0.15828
Drip irrigation coverage	NHP	**0.68181**	NHP	**0.7092**
Temperature in the area	NHP	0.00567	NHP	0.00364
Precipitation in the area	NHP	0.0344	NHP	0.0414
Valorisation of all treated WW	CNO	**0.56212**	ELP	**0.8222**
No of plants in AGF	Biodiversity	**0.7152**	Biodiversity	**0.86008**
Expected yield in AGF	ICR	0.07251	ICR	0.1104
Market price of food	ICR	0.02912	ICR	0.03772

The results of Table 5.3 indicate that 14 out of the 48 selected indicators are the most sensitive to changes in input variables according to the main indices (i.e. CWI, ELC, CNO, EUI, ELP, ChI_{fu} EDM, CCF, CNI, COMF, WDM, NHP, biodiversity and ICR), while according to the total indices, 12 out of the 48 indicators are the most sensitive to changes in input variables –

i.e. CWI, ELC, CPO, ELP, REC, EDM, CNI, COMF, WDM, NHP, biodiversity and ICR. These indicators are the most likely to play a key role in the overall circularity performance of the system. Additionally, when the influenced indicators of the main and total indices are compared, it is evident that 8 variables (highlighted in blue) influence different indicators, indicating that the developed model successfully captures the occurrence of various interdependencies between different system's components.

5.3.3 Scenario Analysis – Dynamic Assessment of Circularity Performance

For the selection of the scenarios that are tested to investigate how the circularity performance of the system changes under different operational conditions, the five identified influential variables (presented in bold in Table 5.3) are classified into two main categories. The first category includes variables that are controllable by system's operators; i.e. drip irrigation coverage and valorisation of the remaining treated wastewater. The second category includes variables that are not controllable by system's operators; i.e. flowrate of influent WW, influent concentration of COD and number of plants in the agroforestry. This differentiation is made to investigate which controllable scenario (i.e. scenarios that consider changes in the controllable variables) obtains better circularity performance, and if the non-controllable scenarios (i.e. scenarios that consider changes in the non-controllable variables) pose a risk of circularity performance failure. This way, optimization of system's operation by both increasing the overall circularity performance and reducing the materialization of risk is suggested. Based on these considerations, the following scenarios are investigated:

- Scenario 0 (current, HYDRO system): current operational condition of the HYDRO system – Appendix Construction Phase Circularity Performance Indicators
- Scenario 1 (controllable): only drip irrigation is used; the remaining treated wastewater is valorised; all the remaining variables are the same with Scenario 0
- Scenario 2 (controllable): only open channels irrigation is used; the remaining treated wastewater is valorised; all the remaining variables are the same with Scenario 0
- Scenario 3 (non-controllable): minimum COD concentration; minimum number of plants in agroforestry; all the remaining variables are the same with Scenario 0

- Scenario 4 (non-controllable): maximum COD concentration; maximum number of plants in agroforestry; all the remaining variables are the same with Scenario 0
- Scenario 5 (integrated): integration of best controllable scenario and worst non-controllable scenario to investigate the alleviation of negative impacts

The circularity performance of the HYDRO system based on the dynamic assessment of the six investigated scenarios is presented in Table 5.4. The results indicate that the best circularity performance of the system is achieved with Scenario 1 (controllable), while Scenario 3 (non-controllable) poses a risk to the overall circularity performance of the system by obtaining the worst values for most of the indicators. Therefore, Scenario 5 (integrated) integrates Scenario 1 and 3 to investigate whether or not the negative impacts resulted from Scenario 3 can be mitigated with changes to specific controllable variables (i.e. operational condition of Scenario 1).

Table 5.4: Circularity Performance results of the HYDRO system for the different investigated scenarios. Green shading: best indicator performance; Red shading: worst indicator performance; Yellow shading: risk; Grey shading: static indicator; Grey font: main and additional functionalities' indicators; ↑: improved indicator performance; ↔: unchanged indicator performance

Indicator Category	Indicator	Scenario 0 (current)	Scenario 1 (controllable)	Scenario 2 (controllable)	Scenario 3 (non-controllable)	Scenario 4 (non-controllable)	Scenario 5 (integrated)
Water	CWI	1.00	1.00	1.00	0.81	1.00	0.81 ↔
	CWO	0.51	0.88	0.82	0.04	0.71	1.00 ↑
	CWF	0.75	0.94	0.91	0.42	0.85	0.90 ↑
	WWR	0.59	1.00	1.00	0.04	0.90	1.00 ↑
	WDM	0.10	0.20	0.00	0.98	0.05	0.98 ↔
	SWE	0.63	0.69	0.58	0.91	0.63	0.91 ↔
	NHP	0.55	0.42	0.68	0.00	0.57	0.00 ↔
	ELW	1.30	2.44	2.22	1.00	1.48	28.31 ↑
Energy	REC	0.23	0.23	0.23	0.16	0.29	0.16 ↔
	ESS	0.23	0.23	0.23	0.16	0.29	0.16 ↔
	EDM	-0.02	-0.02	-0.02	0.02	-0.05	0.02 ↔
	EPE	0.85	0.85	0.85	0.85	0.85	0.85
Resource Inflows & Outflows	CCI	1.00	1.00	1.00	1.00	1.00	1.00
	CCO	0.53	0.54	0.54	0.44	0.59	0.45 ↑
	CCF	0.77	0.77	0.77	0.72	0.79	0.72 ↔
	ELC	1.63	1.65	1.65	1.54	1.68	1.57 ↑
	CNI	1.00	1.00	1.00	0.65	1.00	0.65 ↔
	CNO	0.61	0.86	0.82	0.48	0.69	0.94 ↑
	CNF	0.80	0.93	0.91	0.57	0.84	0.79 ↑

	ELN	1.27	1.84	1.77	1.04	1.50	1.99 ↑
	CPI	1.00	1.00	1.00	1.00	1.00	1.00 ↔
	CPO	0.52	0.89	0.83	0.12	0.75	0.90 ↑
	CPF	0.76	0.95	0.92	0.56	0.88	0.95 ↑
	ELP	1.37	2.75	2.44	1.00	1.75	4.63 ↑
	COMF	0.66	0.66	0.66	0.38	0.83	0.38 ↔
	CChF	0.89	0.89	0.89	0.88	0.89	0.88 ↔
Waste & Emissions	WEI	0.50	7.11	3.69	0.0003	1.34	2564.88 ↑
	EEI	1329.84	3728.09	3647.33	1.00	2390.68	4751.35 ↑
	WUI	0.34	0.88	0.79	0.00	0.57	1.00 ↑
	EUI	0.54	0.59	0.59	0.44	0.60	0.55 ↑
	CF	132461.21	131147.73	130670.19	117413.34	145948.75	115683 ↑
	CF (energy reuse)	121507.16	120193.68	119716.14	110074.80	131783.81	108344 ↑
Biodiversity	Biodiversity	0.74	0.74	0.74	0.00	0.74	0.00 ↔
Economic	ICS	2,314 €	2,160 €	2,634 €	909 €	3,723 €	950 € ↑
	ICR	56,857 €	58,842 €	58,451 €	1,750 €	111,965 €	4,751 € ↑
	TR	95,732 €	97,717 €	97,326 €	40,625 €	150,840 €	43,626 € ↑
	LR	1,949 €	159 €	159 €	3,384 €	513 €	384 € ↑
	PP	4.67	4.51	4.54	126.22	2.38	51.57 ↑
	PP (energy reuse)	4.57	4.42	4.44	89.99	2.35	44.29 ↑
Technical	PF_{fu}	0.57	0.57	0.57	0.00	1.15	0.00 ↔
	PC_{fu}	0.18	0.18	0.18	0.18	0.18	0.18 ↔
	PE_{fu}	1.79	1.79	1.79	1.20	2.32	1.20 ↔
	PIW_{fu}	0.39	0.96	0.96	0.00	0.78	0.96 ↑
	DW_{fu}	0.58	0.00	0.00	0.96	0.19	0.00 ↑
	WWR_{fu}	0.82	1.33	1.45	0.04	1.59	1.00 ↑
	ChI_{fu}	0.67	0.67	0.67	0.45	0.87	0.45 ↔
	CF_{fu}	8.52	8.43	8.40	7.55	9.39	7.44 ↑
	ICR_{fu}	3.66	3.78	3.76	0.11	7.20	0.31 ↑

A comparison between Scenario 0, 1 and 2 indicate that Scenario 0 (i.e. the current operational conditions) achieves the lowest overall circularity performance by obtaining either the same or worst indicator values compared to the other two scenarios. The best circularity performance is achieved with Scenario 1 for which, 28 out of the 48 indicators have the best circularity performance, 19 indicators obtain the same results between all 3 scenarios, and only the ICS indicator achieves the worst performance. All the indicators that target the main and additional functionalities of the system obtain the best or the same results with Scenario 1, apart from WWR_{fu} that performs better under Scenario 2. Scenario 2 further achieves better performance for the CF and ICS indicators compared to the other two controllable scenarios. Open channels that operate in Scenario 2 consume slightly less energy compared to the drip irrigation system.

Although this change in energy consumption is not enough to be depicted in the energy-related indicators, it contributes to the result of the CF and ICS indicators.

Regarding the non-controllable scenarios (i.e. Scenario 3 and 4), it is interesting to note the main changes that would occur in the system under Scenario 4 due to a potential increase of the influent COD concentration. Such change results in an increase to the REC, ESS and PE_{fu} indicators that is not reported with any other tested scenario. Although the influent COD concentration is a non-controllable variable, many scientific studies suggest the co-digestion of sewage with other agro-industrial by-products (Maragkaki et al., 2017) or food waste (Iacovidou et al., 2012) to increase biogas production and therefore, energy production onsite. Additionally, it is evident that if the conditions of Scenario 3 occur in the system and increased risk to circularity failure would be posed for 32 out of the 48 indicators. Under the occurrence of Scenario 3, all the values of the indicators that target the main and additional functionalities are significantly deteriorated to such an extent that the system no longer has a circular behaviour for many of these indicators (i.e. WWR is almost zero; ELW, ELN and ELP are equal to 1; WUI is zero; ICR is almost negligible; PP are significantly extended; PF_{fu} and PIW_{fu} are zero; and DW_{fu} is almost 1).

The negative impacts of Scenario 3 can be overcome to a large extent if the controllable operational conditions are switched to Scenario 1 as indicated in Scenario 5 (integrated) results. Under Scenario 5 (integrated), the system manages to significantly reduce the impacts related to water, resources, waste & emissions, and most of the technical indicators. Negative impacts remain mainly for the biodiversity, PF_{fu} and economic indicators. These results indicate the indirect connection between biodiversity and economic indicators. Since biodiversity cannot be controlled by system's operators, further investigation is required to better understand the complex natural processes, the interconnections between them, as well as the feedback loops that they create to the anthropogenic system. Investigation and better understanding of these feedback loops are expected to result in additional suggestions that would further improve circularity performance of the system.

5.4 Relation with the Sustainable Development Goals

The relation of the selected indicators with the SDGs is presented in Figure 5.4. The results of Figure 5.4 indicate that the selected indicators mainly target – in descending order – SDG6 of clean water and sanitation, SDG7 of affordable and clean energy, SDG12 of responsible consumption and production, SDG8 of decent work and economic growth, and SDG15 of life on land. The selected indicators also target SDG9 of industry innovation and infrastructure, SDG1 of no poverty, SDG3 of good health and well-being, SDG11 of sustainable cities and communities, SDG13 of climate action, SDG4 of quality education, SDG2 of zero hunger, and SDG16 of peace justice and strong institutions. Only four out of the seventeen SDGs are not covered by the selected indicators, i.e. SDG5 of gender equality, SDG10 of reduced inequalities, SDG14 of life below water, and SDG17 of partnerships for the goals. Although some additional indicators can be considered in order to cover all the SDGs (especially social indicators related to inequalities), it is evident that the selected set of indicators successfully assesses most of sustainability aspects.

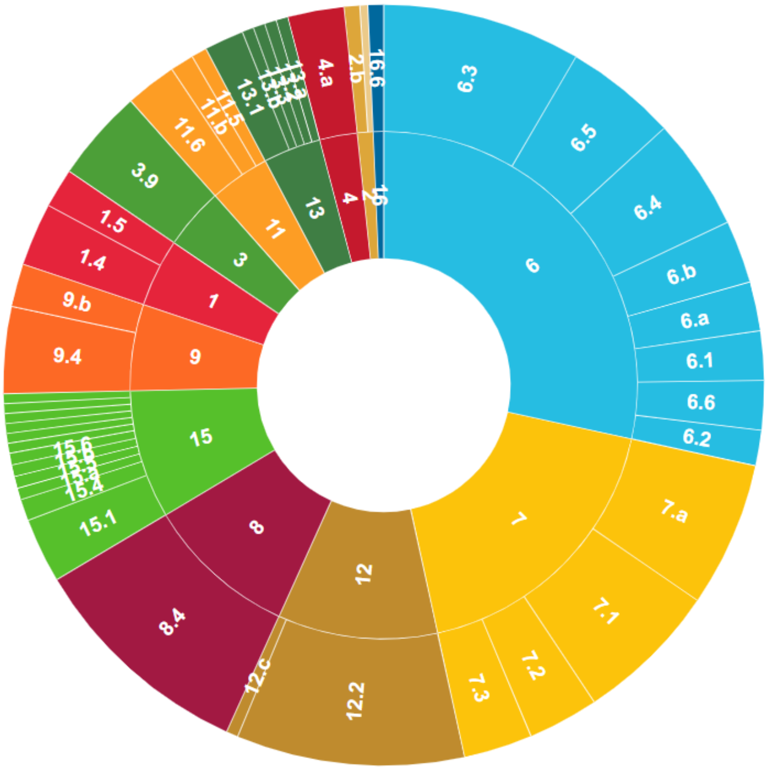


Figure 5.4: Representation of the relative weight of the SDGs and targets measured by the selected indicators

5.5 Summary of main findings

The current work develops an operationalization of the Multi-Sectoral Water Circularity Assessment framework for systems under the WEFE nexus. The developed methodology includes a systematic for the selection of circularity and sustainability indicators. This is achieved by considering the purpose and scale of the assessment, the system boundaries, the main and additional functionalities of the system, as well as additional benefits and costs, the three CE principles and the SDGs. The circularity assessment of the system is differentiated between benchmark and dynamic assessment. The former focuses on the comparison between the baseline scenario and the new configuration of the system (HYDRO) – coupling grey infrastructure with NBS – while the latter targets system's optimization in order to achieve improved circularity performance. For this purpose, the selected indicators are subjected to sensitivity analysis to: i) identify whether or not the selected indicators are sensitive to changes, ii) identify which operational variables affect system's circularity the most, and iii) develop alternative scenarios investigating changes in circularity performance that enable suggestions for system's optimization. This is a versatile methodology that can be implemented in different systems/case studies.

In the current work, the developed methodology is applied in a real case study falling under the WEFE nexus, developed within the HYDROUSA H2020 project. The benchmark assessment results indicate that the HYDRO system obtains a better circularity performance compared to the baseline scenario. The CF_{fu} of the HYDRO system is already slightly better, however, if the sequestrated carbon is considered in the calculation, the CF_{fu} value is expected to be further improved. The results of the sensitivity analysis show that among the 48 selected indicators only 3 could not capture changes that may occur in the system, and that 5 controllable and non-controllable variables affect the system's circularity performance the most. The results of the dynamic assessment indicate that the system does not operate under its optimum conditions and in order to improve its circularity performance it should switch to Scenario 1 (controllable). Scenario 3 (non-controllable) represents a risk of circularity performance failure of the system if it operates under the current conditions, but the negative impacts can be mitigated if the operational conditions of Scenario 1 are implemented. Although Scenario 1 achieves optimum circularity performance for most of the selected indicators, actions targeting improvement of the produced energy, as well as investigation of feedback loops that occur in the natural environment and further impact the anthropogenic system are further required for the system to reach the optimum overall circularity performance. Finally, the selected indicators are related to 13 out of the 17 SDGs, which further highlights the dual achievement of simultaneously assessing circularity and sustainability.

6. Conclusions and Recommendations for future research

6.1 Conclusions of the study

Water as one of the key priority areas for CE indicated by the new Circular Economy Action Plan faces unique circularity challenges mainly due to its regional nature, its undervalued price, its interconnection with various socio-economic sectors (i.e. nexus), the interdependencies between the natural and anthropogenic systems, and the different resources incorporated with or embodied in water. This thesis demonstrated that water specificities play a key role in the way water circularity should be approached in order to holistically and systemically measure and evaluate CE in water, and avoid burden shifting. This research followed a twofold approach to the topic of water circularity assessment by building the context of water circularity (i.e. conceptual approach) and by developing and applying a water circularity assessment methodology that includes circularity performance indicators (i.e. operational approach). This way, a sound scientific basis of the complex issue of water circularity is established, providing systematic and holistic guidelines to practitioners.

In Chapter 2, a literature review is conducted to answer two main research questions. The first research question is related to what needs to be measured to assess circularity in water systems. Based on the context of CE in water as provided by three white papers, at the core of a circularity assessment for water systems lies the realization of the three CE principles of natural capital regeneration, keeping resources in use and designing out negative externalities. The water, nutrients, energy and other resources pathways need to be followed within both human-managed and nature-managed systems, enabling the consideration of physical, environmental, social and economic aspects. The second question is related to the state-of-the-art in frameworks, methodologies, tools and indicators to measure and assess circularity in water systems, considering the identified principles, pathways and aspects. The results of the literature review concerning that question revealed that: i) there is no single available circularity assessment method or tool that can holistically measure and evaluate all the required aspects for water systems (e.g. physical, technical, ecological, social, etc.), ii) circularity assessment in water mainly focuses on nano (i.e. specific technologies), micro (e.g. WWTP) or symbiosis between WWTPs and other industries by targeting the anthropogenic system only, iii) holistic approaches considering both human-managed and nature-managed systems are not available for assessing circularity in water, and iv) NBS that can play a key role in the transition to circular water systems are not evaluated from a circularity perspective. The examined methodologies and tools indicated that the most common methods to CE assessment are MFA, LCA and LCC (or other similar economic valuation methods). However, these methods fail to capture the actual impacts of CE to the natural systems (e.g. biodiversity, water quantity and quality improvement of natural resources, etc.). Therefore, additional methods are required in order to fully cover the water circularity aspects (e.g. simulation models, such as hydro-biogeochemical models, or other analytical tools, such as ecosystem services assessment, natural capital accounting). Additionally, this research highlighted the need of using available indicators, not specifically developed for circularity assessments in order to communicate the results of circularity performance of a water system. An integrated approach to measure and assess circularity of complex water systems is evidently one of the main gaps of the existing literature, along with a targeted water circularity assessment framework.

The lack of a water circularity assessment framework – identified in Chapter 2 – is addressed in Chapter 3 by developing a holistic and systemic water circularity assessment framework, namely Multi-Sectoral Water Circularity Assessment (MSWCA). The development of such framework sets the guidelines that need to be followed and the tasks that need to be performed for assessing circularity performance of water systems (i.e. the research question of Chapter 3). The MSWCA framework breaks the artificial sectoral boundaries of the existing evaluation methods and assesses circularity of multi-sectoral systems of the Water-Energy-Food-Ecosystems nexus by including various socio-economic (i.e. water, agro-food, energy, industrial, and waste-handling) and non-economic (i.e. natural environment) sectors. The MSWCA provides guidelines for considering the multiple interdependencies between the different socio-economic sectors, as well as the feedback loops between the socio-economic sectors and the natural environment. Additionally, the MSWCA framework considers the symbiotic management of the different resources incorporated in the nexus (e.g. water, energy, nutrients, etc.). The tasks that need to be performed are further explained in the developed framework by including a detailed methodological process that consists of five distinctive stages, providing a systematic way to assess circularity of complex systems. The framework addresses issues of data requirements, uncertainty and sensitivity analysis of the results, appropriate economic valuation methods to cover both the value in and the value of water. It also develops an indicators database that includes existing and newly developed indicators that can serve as a first step for the selection of appropriate indicators when assessing circularity of multi-sectoral systems. The framework suggests the integration of existing methodologies and tools into a single modelling framework and provides a detailed list of methods and tools that can be incorporated in the integrated model depending on its purpose. The integration of different methods and tools allows the consideration of all the different aspects (e.g. physical, technical, environmental/ecological, economic, etc.) required for a systemic circularity assessment and effectively measure the three CE principles.

Multi-sectoral circularity implementation, measuring and assessment involves various and different stakeholders (i.e. industrial actors, academics, policy-makers). It is therefore evident that their needs and perceptions may significantly affect the assessment and the selection of indicators. To avoid both an undesired self-selection of indicators by practitioners based on their own needs and a set of indicators that are not meaningful to the relevant stakeholders, a dynamic approach to indicators prioritization process is further developed in this study. This dynamic and structured approach is based on Interpretive Structural Modelling and MICMAC analysis and combines experts' opinion and participatory activities, bringing together all relevant stakeholders to consider their views on appropriate indicators for the Water-Energy-Food-Ecosystems nexus. The developed methodology used the set of the MSWCA indicators (as an indicative set of indicators), which were ranked by relevant industrial stakeholders and experts identified their direct contextual relationships, answering the research question of Chapter 4 on how to combine scientific knowledge and the practical needs of industrial stakeholders for the prioritization of appropriate circularity indicators. Interpretive Structural Modelling and MICMAC analysis enable the visualization of the hierarchical structure of the indicators – based on the identification of the importance level of the indicators – as well as the investigation of interrelationships between them – based on the driving and dependence power of each indicator. This approach is expected to help researchers, practitioners, and policymakers to prepare and execute CE strategically, as well as define and use relevant metrics to assess and evaluate CE in a systematic way. The developed methodology can be used to validate and identify the importance of various sets of indicators, indicating its applicability to the indicators prioritization process for different systems.

In Chapter 5, an operationalization of the MSWCA framework is performed by applying it to a real case study developed in HYDROUSA H2020 project. The operationalization to the topic of water circularity assessment shows how to implement in practice the MSWCA framework, and it further enables the development of a systematic methodological process for the selection of appropriate circularity and sustainability indicators. The developed indicators selection process helps answering the first research question of Chapter 5 on what aspects need to be considered to select appropriate indicators. Following the methodological phases of the MSWCA framework, it was found that the System Development phase represents the most critical step for a scientific justification of appropriate indicators selection. In this phase, a clear definition of the assessment scope, system's multi-functionality, system's boundaries and circularity conceptualization is performed. Considering the scope of the assessment and the system's boundaries, appropriate indicators are carefully selected targeting the main system's functionality, the additional functionalities of the system, as well as additional benefits and costs (including physical, environmental, economic and social) resulting in the system. The selected indicators are then compared to the three CE principles to ensure the indicators' adequateness to represent all three of them. The final list of indicators – consisting of 46 operational circularity performance indicators – is then categorized into resource, water, energy, waste and emissions, economic and other related indicators and their relation with the 17 SDGs is identified to ensure that the selected indicators are able to cover sustainability aspects. To answer the second research question of Chapter 5, two types of circularity assessment are conducted. A benchmark circularity assessment is used to compare the circularity performance of a new system to the circularity performance of a refence scenario, enabling the evaluation of strategic interventions. On the other hand, a dynamic circularity assessment is performed to optimize system's operation by comparing the circularity performance achieved under different operational scenarios. Both types of circularity assessment were implemented in the HYDROUSA case study. Although the results of the benchmark assessment indicate that the new configuration of the system (i.e. HYDRO system) has an improved circularity performance, the results of the dynamic assessment show that the HYDRO system is not operated under the optimum conditions. Optimization of HYDRO system's operation can be achieved if drip irrigation is used as the only irrigation method and all treated wastewater is valorised. The results of this Chapter highlight the key role of interdependencies between the different system components in affecting the overall circularity performance. Although various interdependencies between the different anthropogenic components are considered in this Chapter – enabling suggestions for system's optimization –

the consideration and modelling of feedback loops that occur in the natural environment – impacting the anthropogenic system and affecting the long-term circularity performance of the system – need further investigation. This way, better understanding of system's behaviour would be achieved enabling strategic decision-making for circularity improvement of complex water systems.

The outcomes of this thesis are believed to add value to the way water circularity is approached, implemented, measured and evaluated. Systemic thinking, multi-sectoral interdependencies, natural and anthropogenic feedback loops, symbiotic management of resources and clear circularity targets and objectives are the cornerstones of CE in complex water systems. Following this approach, a great opportunity arises, i.e. to break the artificial sectoral boundaries and enable a collective thinking and an in-depth transformation that would allow us to address cross-cutting challenges leading to a more resilient future.

6.2 Recommendations for future work

In the current thesis, efforts were focused on the investigation of the concept of CE in water and of methods, tools and indicators to holistically and systemically measure and assess circularity in systems of the Water-Energy-Food-Ecosystems nexus. The main aspect of the analysis was to investigate how the development of a holistic framework that covers the complexities and specificities of water can facilitate circularity assessments and result in meaningful indicators. After the development of the MSWCA framework, the analysis was focused on the framework's practical applicability following two main research axes: i) development of a participatory approach to engage stakeholders in the prioritization of pre-selected indicators, and ii) ex-post circularity and sustainability assessment of real case studies, following the MSWCA framework, to develop a systematic indicators selection methodology and to gain insights of different circularity assessment types that can be used for different purposes. The results of the first research axis showed that ISM combined with MICMAC analysis is a powerful tool that enables the participation of various stakeholders and can be used to identify and better understand the complex interrelationships between different indicators, enabling their prioritization. The results of the operationalization of the MSWCA framework (second research axis) showed the need of a systematic indicators selections process carefully considering the assessment scope and system's boundaries in order to develop indicators accounting for system's multi-functionality, the 3 CE principles and the 17 SDGs. The developed indicators-based assessment tool – based on process modelling – enabled the investigation of various interdependencies between the different system's components and differentiated between benchmark and dynamic circularity assessment of the system. The results of the benchmark assessment facilitated the comparison in terms of circularity performance between the newly-developed system and a reference scenario, while the dynamic assessment results evaluated the circularity performance of different operational scenarios enabling system's optimization.

The developed indicators-based model considers the interdependencies between different components of the system by simulating all the anthropogenic processes occurred in the system and to a lesser extent some fast natural processes (e.g. the hydrological cycle). Slow natural processes that are more complex and take more time to evolve are not mathematically described in the developed model and therefore, the natural feedback loops are not simulated. The investigation of natural system's behaviour by simulating the mechanisms that drive the natural feedback loops would enhance the understanding on how nature operates and how these feedback loops would further impact the anthropogenic system and potentially change circularity performance of the system in the future. This would require the integration of natural system models to human system models that would allow the interaction between the coupled models (i.e. the output of the first one becomes the input of the second model, continuing in simulation loops), simulating the behaviour change of both systems during the years. The results of such integration that would follow a complete systems' thinking are expected to strengthen system's improvement towards a more sustainable operation, holistically considering all the required technical, ecological, economic and social aspects.

The indicators selection exercise developed in this thesis and applied to the HYDRO system resulted in a set of 46 operational indicators. These 46 indicators were required to effectively describe and assess the main functionality, the additional functionalities and the additional benefits and costs of the system, as well as all incorporated resources, waste and emissions, economic, social and ecological aspects of the system, the 3 CE principles and finally representing 14 out of the 17 SDGs. Evidently, the development of these 46 indicators resulted in a holistic circularity and sustainability assessment however, the incorporation of an increased number of indicators may hinder their wider adoption and use for decision-making. Future research should therefore focus on the construction of composite circularity performance indicators for the Water-Energy-Food-Ecosystems nexus. In Chapter 4, it was found that the investigated circularity performance indicators have different importance levels. In Chapter 5, it was shown that it is not possible to achieve best results for all the incorporated indicators simultaneously due to the various interdependencies that occur in the system and thus, decisions were made based on the results of the indicators related to system's multi-functionality mainly. These results indicate that not all the incorporated indicators contribute equally to the measurement and evaluation of the total circularity performance of the system. Therefore, a weighting system can be defined to assign weights to the different indicators that will be used to estimate an individual aggregate score of circularity performance. For this purpose, decisions should be made on what type of weighting (i.e. equal or differential) and what weighting approaches are required, considering the theoretical framework that forms the foundations for measuring the complex characteristics of the aggregate indicators system, the importance and contribution of each incorporated indicator to the overall circularity performance – that may depend on local conditions, stakeholders views and goals, etc. – and data quality as well as statistical adequacy of the incorporated indicators. On one hand, statistical approaches such as Correlation Analysis, Principal Component Analysis and others can be used to assign weights based on the objective principle. On the other hand, subjective weights can be assigned by using methods that make combined comparisons, e.g. Multi-Attribute Decision Making, Analytic Hierarchy Process, Multi-Attribute Compositional Models, Conjoint Analysis, etc. The development of an aggregate score of circularity performance for the WEFE nexus can be widely used as a tool for multiple purposes (from decision-making to communication of circularity performance to the public and ranking) due to its simplicity in summarizing the circularity performance results in an easily understandable manner that facilitates evaluation and comparison.

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List of publications

The thesis is based on the following publications and conference presentations:

Publications

- Katsou, E., **Nika, C. E.**, Buehler, D., Marić, B., Megyesi, B., Mino, E., ..., Atanasova, N., 2020. Transformation tools enabling the implementation of nature-based solutions for creating a resourceful circular city. Blue-Green Systems 2(1), 188-213. https://doi.org/10.2166/bgs.2020.929
- **Nika, C. E.**, Gusmaroli, L., Ghafourian, M., Atanasova, N., Buttiglieri, G., Katsou, E., 2020. Nature-based solutions as enablers of circularity in water systems: A review on assessment methodologies, tools and indicators. Water Research 183, 115988. https://doi.org/10.1016/j.watres.2020.115988
- **Nika, C. E.**, Vasilaki, V., Expósito, A., & Katsou, E., 2020. Water Cycle and Circular Economy: Developing a Circularity Assessment Framework for Complex Water Systems. Water Research 187, 116423. https://doi.org/10.1016/j.watres.2020.116423
- Atanasova, N., Castellar, J. A., Pineda-Martos, R., **Nika, C. E.**, Katsou, E., Istenič, D., ..., Langergraber, G., 2021. Nature-Based Solutions and Circularity in Cities. Circular Economy and Sustainability, 1-14. https://doi.org/10.1007/s43615-021-00024-1
- UKWIR. What does a circular economy water industry look like? Published by UK Water Industry Research Limited, 3rd Floor, 36 Broadway, Westminster, London, SW1H 0BH. (**co-author**)
- **Nika, C. E.**, Expósito, A., Kisser, J., Bertino, G., Oral, H. V., Dehghanian, K., ..., Katsou, E., 2021. Validating Circular Performance Indicators: The Interface between Circular Economy and Stakeholders. Water 13(16), 2198. https://doi.org/10.3390/w13162198
- **Nika, C.E.**, Vasilaki, V., Renfrew, D., Danishvar, M., Echchelh, A., Katsou, E., 2022. Assessing circularity of multi-sectoral systems under the Water-Energy-Food-Ecosystems (WEFE) nexus. Submitted to Water Research Journal for publication.

Conference presentations

- **Nika C.E.**, Stanchev P., Katsou E., 2019. Measuring the circularity potential of an eco-friendly touristic facility in a Mediterranean island. Oral presentation on the 3rd IWA Resource Recovery Conference, Sep 8-12 2019, Venice, Italy.
- COST Action Circular City. 7th Virtual Circular City workshop, 17 Feb 2021.
- **Nika C.E.**, Vasilaki V., Katsou E., 2021. The Multi-Sectoral Water Circularity Assessment (MSWCA) Framework. Oral presentation on the IWA Ecotechnologies for Wastewater Treatment, Jun 23-25 2021, Milan, Italy.
- Katsou E., Atanasova N., Vasilaki V., **Nika C.E.**, Pergar P., 2021. Workshop: Implementing nature-based solutions for creating a resourceful circular city – measuring

and assessing circularity. Workshop on the IWA Ecotechnologies for Wastewater Treatment, Jun 23-25 2021, Milan, Italy.

- **Nika C.E.**, Stanchev P., Vasilaki V., Katsou E., 2022. Water Circularity Assessment Framework. Accepted for oral presentation on the IWA World Water Congress & Exhibition, Sep 11-15 2022, Copenhagen, Denmark.

Appendix A – Chapter 3

The indicators database can be found either in the attached Supplementary Material or online using the following link: https://doi.org/10.1016/j.watres.2020.116423

Appendix B – Chapter 4

B.1 Questionnaire

Introduction

The following is a research questionnaire aimed at identifying, shortlisting, and validating key Circularity Performance Indicators (CPI's) which can be used as metrics in a multi-sectoral circularity assessment framework. It is a part of a PhD research – funded by H2020 project HYDROUSA and supported by COST Action CA17133 Circular City – being completed at Brunel University London. We invite you to take participate in the survey as a key stakeholder within your sector. Through this medium you will be able to speak about your organisation's circular economy strategies and assist to achieve the questionnaire/research objective. The survey will not require any form of identification from you or the organization you represent, as well as the data will be presented anonymously.

Questions

1. Please specify the country where your organization is incorporated in:

- ☐ United Kingdom
- ☐ Spain
- ☐ France
- ☐ Germany
- ☐ Austria
- ☐ Italy
- ☐ Greece
- ☐ Turkey
- ☐ Other, please specify: ___________________________________

2. Please select the sector/category under which your organization is fallen:

- ☐ Urban Water sector

- ☐ Energy sector
- ☐ Agro-food sector
- ☐ Waste handling sector (solid waste)
- ☐ Local/Regional/National bodies/authorities/agencies
- ☐ Consultancies

3. Is the organisation interested in having a positive impact on the following circular economy principles?

- ☐ Regenerate natural capital
- ☐ Keep resources in use
- ☐ Design out waste externalities
- ☐ None of the above

4. Please rate the following indicators from 1 to 3 (1 – not interested at all, 2 – could potentially be used, 3 – highly interested):

Category	Indicators	Description	Please rate the indicator from 1 – 3
Natural Capital Regeneration	regenerative capacity index	The safe operating limits (i.e. thresholds) of nature at a local/regional level that should not be crossed	
	hydrological performance	Evaluation of the restoration of natural hydrological flows (runoff, evapotranspiration, infiltration) at the local level	
	water stress	Indication of water scarcity at the local level	
	reduction of qualitative water withdrawals	Indicates the improvement in water quality at the local level	
	gross P balance	Evaluates the phosphorus cycling performance by indicating P surplus at the local level	
	gross N balance	Evaluates the nitrogen cycling performance by indicating N surplus at the local level	
	C balance	Evaluates the carbon cycling performance by indicating C emissions and C storage and sequestration at the local level	
	soil condition improvement	Evaluates the actual soil condition improvement at the local	
	index of biodiversity	Evaluates the state of biodiversity at the local	
	gain and loss of natural and semi-natural areas	indicates the conversions of (semi-)natural vegetated areas to other types of land use/cover and vice versa at the local level	
	revenues/savings from natural capital regeneration	indicates the revenues or savings from natural capital regeneration at the local level	
Keep Resources in Use	Circular Index (CI)	Evaluates circularity of products/resources/materials based on the following 2 indicators (Circular Use & Flow)	
	Circular Use (CU)	Considers the contribution of life cycle extension, sharing and "product as a service" to circularity	
	Circular Flow (CF)	Considers the circularity of all input and output flows	
	Maximum Achievable Circularity	The maximum degree to which the system can potentially close its loops (considering legislative issues, product specifications, etc.)	

	Cost savings from circularity measures	Savings from the implementation of CE both at local and organizational / sectoral levels	
Design Out Waste Externalities	PRoduct Index (PRI)	A measure of the ratio of resources consumed that are returned as a useful product	
	WAste Index (WAI)	A measure of the ratio of resources consumed that is returned as a waste for disposal	
	Total Waste Reduction	Measures waste reduction achieved in the system due to circularity measures	
	Total Air Emissions Reduction	Measures air emissions reduction achieved in the system due to circularity measures	
	Total Water Emissions Reduction	Measures water emissions reduction achieved in the system due to circularity measures	
	Total Soil Emissions Reduction	Measures soil emissions reduction achieved in the system due to circularity measures	
	Revenues/savings due to minimization of negative externalities	Savings and revenues from minimization of negative externalities	

5. Are there any other circularity performance aspects that your organisation would be interested in having information on and are not covered by the above presented indicators (e.g. social indicators)

☐ Yes

☐ No

If yes, please specify:

____

The same questions were asked to academics participating to the COST Action Circular Cities Workshop.

Questionnaire Results

- Response to Question 1, “country of organization”:

Table B.1: Number of responses per country

No.	Countries	Responses per country
1	Austria	1
2	Belgium	1
3	Brazil	1
4	Cyprus	1
5	Germany	2
6	Hungary	1
7	Italy	3
8	Serbia	2
9	Spain	8
10	Tunisia	1
11	Turkey	2
12	United Kingdom	8
13	Portugal	2
14	Greece	3
15	Bulgaria	1
16	Slovakia	1
17	France	2

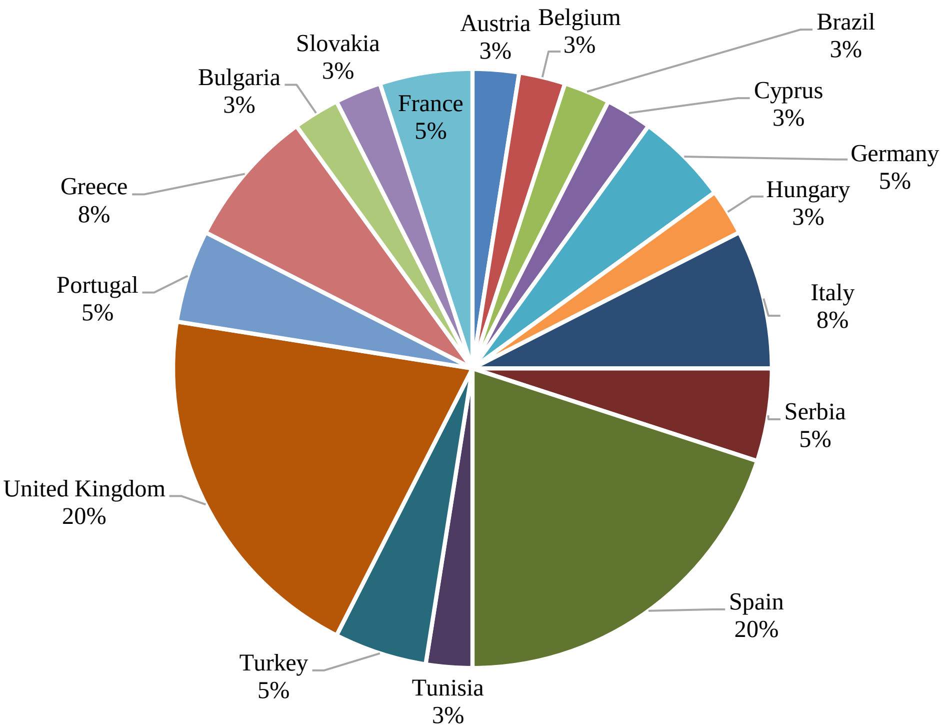

Figure B.1: Distribution of responses per country

- Response to Question 2, “sector of focus”:

Table B.2: Number of responses per sector

Sector	Number of survey participants
Agro-food sector	5
Consultancies	7
Local / Regional / National bodies / authorities / agencies	3
Urban Water sector	7
Energy sector	3
Academics focusing on CE	15
TOTAL	40

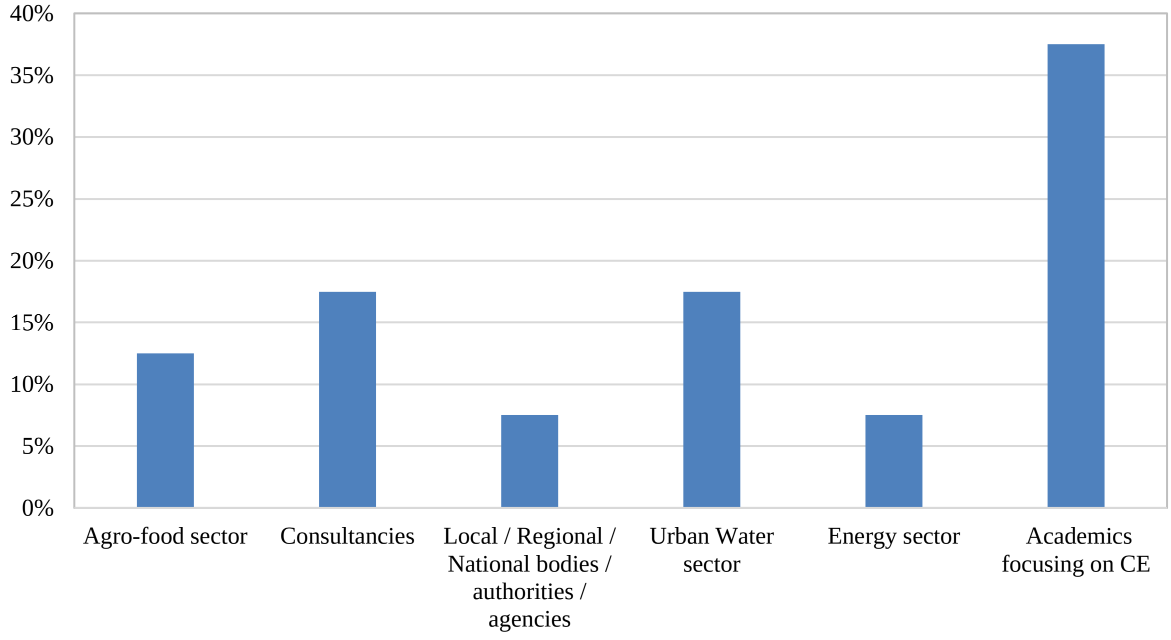

Figure B.2: Distribution per sector

- Response to Question 3, “interest in the CE principles”:

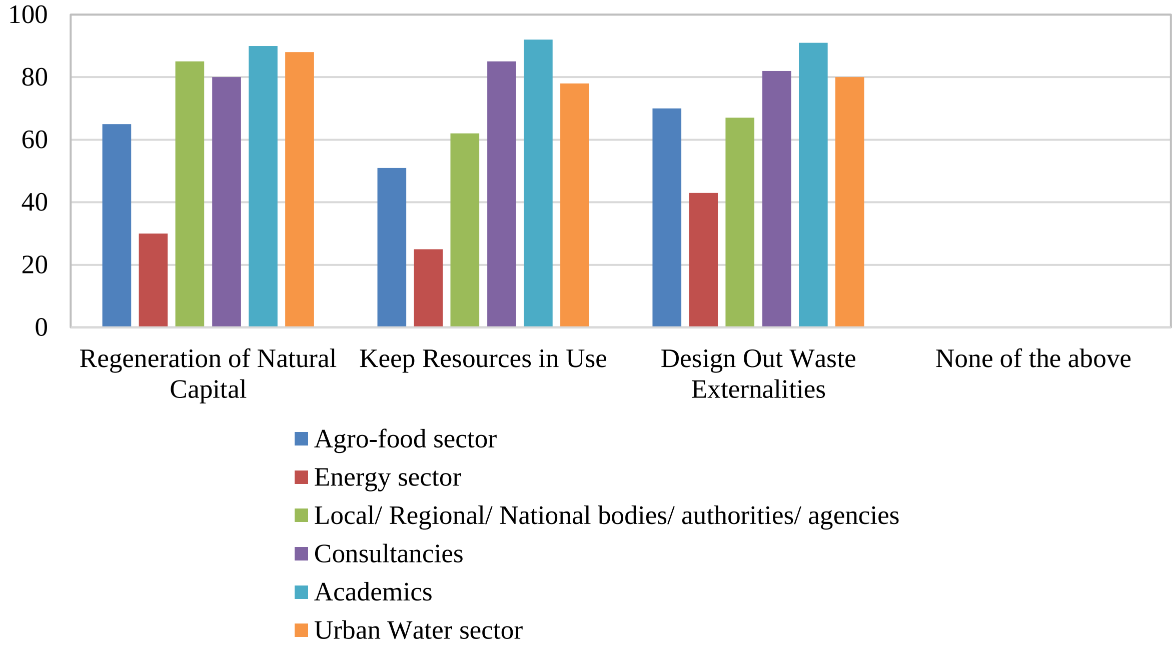

Figure B.3: Interest in CE principles per sector

- Response to Question 5, “any other aspects not covered by the selected indicators”:

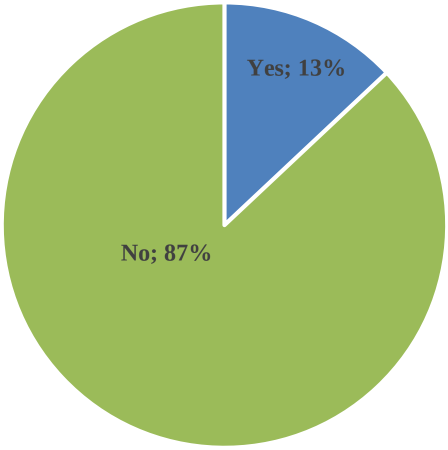

Figure B.4: Interest in any other aspects for CE assessment

B.2 Interpretive Structural Modelling

B.2.1 Reachability Matrix

The initial reachability matrix from the SSIM is developed, by replacing the four symbols (i.e., V, A, X or O) of the SSIM with binary numbers in the initial reachability matrix. The rules for this substitution are the following:

If the (i, j) entry in the SSIM is V, then the (i, j) entry in the reachability matrix becomes 1 and the (j, i) entry becomes 0.

If the (i, j) entry in the SSIM is A, then the (i, j) entry in the matrix becomes 0 and the (j, i) entry becomes 1.

If the (i, j) entry in the SSIM is X, then the (i, j) entry in the matrix becomes 1 and the (j, i) entry also becomes 1.

If the (i, j) entry in the SSIM is O, then the (i, j) entry in the matrix becomes 0 and the (j, i) entry also becomes 0.

Table B.3: Initial Reachability Matrix

CPIs	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	1	0	0	0	0	1	0	1	0	0	0	0	1	1	0	1	0	0	1	1
2	0	1	1	0	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0
3	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	1	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
5	0	0	0	0	1	0	1	0	0	0	1	1	0	0	0	0	0	0	0	0
6	0	0	0	1	0	1	0	0	0	0	0	0	0	0	1	0	0	0	1	1
7	0	0	0	0	1	0	1	0	0	0	1	1	0	0	0	0	0	0	0	0
8	0	0	0	1	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0
9	0	1	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0
10	0	1	0	0	0	1	0	1	1	1	0	0	0	1	0	1	1	1	1	1
11	1	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0
12	1	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0
13	1	0	0	0	0	1	0	1	0	0	0	0	1	1	0	1	1	0	1	1
14	0	0	0	1	0	0	0	1	0	0	0	0	0	1	1	0	0	0	0	1
15	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
16	0	0	0	1	0	0	0	0	0	0	0	0	0	1	1	1	0	0	1	1
17	0	0	0	1	0	1	0	1	0	0	0	0	1	1	1	1	1	0	1	1
18	0	0	0	1	0	0	0	1	0	0	0	0	0	0	1	0	1	1	1	1
19	0	0	0	1	0	1	0	1	0	0	0	0	0	0	1	1	1	1	1	1
20	0	0	0	1	0	1	0	1	0	0	0	0	0	0	1	1	1	1	1	1

B.2.2 Partitioning Levels

Table B.4: First iteration

Indicator	Reachability set	Antecedent set	Intersection set	Iteration and level
1	I1 I3 I4 I6 I8 I13 I14 I15 I16 I17 I18 I19 I20	I1 I2 I5 I6 I7 I9 I10 I11 I12 I13 I14 I16 I17 I18 I19 I20	I1 I6 I13 I14 I16 I17 I18 I19 I20	
2	I1 I2 I3 I4 I5 I6 I7 I8 I9 I10 I11 I12 I13 I14 I15 I16 I17 I18 I19 I20	I2 I9 I10	I2 I9 I10	
3	I3 I4 I15	I1 I2 I3 I4 I5 I6 I7 I8 I9 I10 I11 I12 I13 I14 I15 I16 I17 I18 I19 I20	I3 I4 I15	***I***
4	I3 I4 I15	I1 I2 I3 I4 I5 I6 I7 I8 I9 I10 I11 I12 I13 I14 I15 I16 I17 I18 I19 I20	I3 I4 I15	***I***
5	I1 I3 I4 I5 I6 I7 I8 I11 I12 I13 I14 I15 I16 I17 I18 I19 I20	I2 I5 I7 I9 I10	I5 I7	
6	I1 I3 I4 I6 I8 I13 I14 I15 I16 I17 I18 I19 I20	I1 I2 I5 I6 I7 I9 I10 I11 I12 I13 I14 I16 I17 I18 I19 I20	I1 I6 I13 I14 I16 I17 I18 I19 I20	
7	I1 I3 I4 I5 I6 I7 I8 I11 I12 I13 I14 I15 I16 I17 I18 I19 I20	I2 I5 I7 I9 I10	I5 I7	
8	I3 I4 I8 I15	I1 I2 I5 I6 I7 I8 I9 I10 I11 I12 I13 I14 I16 I17 I18 I19 I20	I8	
9	I1 I2 I3 I4 I5 I6 I7 I8 I9 I10 I11 I12 I13 I14 I15 I16 I17 I18 I19 I20	I2 I9 I10	I2 I9 I10	
10	I1 I2 I3 I4 I5 I6 I7 I8 I9 I10 I11 I12 I13 I14 I15 I16 I17 I18 I19 I20	I2 I9 I10	I2 I9 I10	

11	I1 I3 I4 I6 I8 I11 I12 I13 I14 I15 I16 I17 I18 I19 I20	I2 I5 I7 I9 I10 I11 I12	I11 I12	
12	I1 I3 I4 I6 I8 I11 I12 I13 I14 I15 I16 I17 I18 I19 I20	I2 I5 I7 I9 I10 I11 I12	I11 I12	
13	I1 I3 I4 I6 I8 I13 I14 I15 I16 I17 I18 I19 I20	I1 I2 I5 I6 I7 I9 I10 I11 I12 I13 I14 I16 I17 I18 I19 I20	I1 I6 I13 I14 I16 I17 I18 I19 I20	
14	I1 I3 I4 I6 I8 I13 I14 I15 I16 I17 I18 I19 I20	I1 I2 I5 I6 I7 I9 I10 I11 I12 I13 I14 I16 I17 I18 I19 I20	I1 I6 I13 I14 I16 I17 I18 I19 I20	
15	I3 I4 I15	I1 I2 I3 I4 I5 I6 I7 I8 I9 I10 I11 I12 I13 I14 I15 I16 I17 I18 I19 I20	I3 I4 I15	***I***
16	I1 I3 I4 I6 I8 I13 I14 I15 I16 I17 I18 I19 I20	I1 I2 I5 I6 I7 I9 I10 I11 I12 I13 I14 I16 I17 I18 I19 I20	I1 I6 I13 I14 I16 I17 I18 I19 I20	
17	I1 I3 I4 I6 I8 I13 I14 I15 I16 I17 I18 I19 I20	I1 I2 I5 I6 I7 I9 I10 I11 I12 I13 I14 I16 I17 I18 I19 I20	I1 I6 I13 I14 I16 I17 I18 I19 I20	
18	I1 I3 I4 I6 I8 I13 I14 I15 I16 I17 I18 I19 I20	I1 I2 I5 I6 I7 I9 I10 I11 I12 I13 I14 I16 I17 I18 I19 I20	I1 I6 I13 I14 I16 I17 I18 I19 I20	
19	I1 I3 I4 I6 I8 I13 I14 I15 I16 I17 I18 I19 I20	I1 I2 I5 I6 I7 I9 I10 I11 I12 I13 I14 I16 I17 I18 I19 I20	I1 I6 I13 I14 I16 I17 I18 I19 I20	
20	I1 I3 I4 I6 I8 I13 I14 I15 I16 I17 I18 I19 I20	I1 I2 I5 I6 I7 I9 I10 I11 I12 I13 I14 I16 I17 I18 I19 I20	I1 I6 I13 I14 I16 I17 I18 I19 I20	

Table B.5: Second iteration

Indicator	Reachability set	Antecedent set	Intersection set	Iteration and level
1	I1 I6 I8 I13 I14 I16 I17 I18 I19 I20	I1 I2 I5 I6 I7 I9 I10 I11 I12 I13 I14 I16 I17 I18 I19 I20	I1 I6 I13 I14 I16 I17 I18 I19 I20	
2	I1 I2 I5 I6 I7 I8 I9 I10 I11 I12 I13 I14 I16 I17 I18 I19 I20	I2 I9 I10	I2 I9 I10	
5	I1 I5 I6 I7 I8 I11 I12 I13 I14 I16 I17 I18 I19 I20	I2 I5 I7 I9 I10	I5 I7	
6	I1 I6 I8 I13 I14 I16 I17 I18 I19 I20	I1 I2 I5 I6 I7 I9 I10 I11 I12 I13 I14 I16 I17 I18 I19 I20	I1 I6 I13 I14 I16 I17 I18 I19 I20	
7	I1 I5 I6 I7 I8 I11 I12 I13 I14 I16 I17 I18 I19 I20	I2 I5 I7 I9 I10	I5 I7	
8	I8	I1 I2 I5 I6 I7 I8 I9 I10 I11 I12 I13 I14 I16 I17 I18 I19 I20	I8	***II***
9	I1 I2 I5 I6 I7 I8 I9 I10 I11 I12 I13 I14 I16 I17 I18 I19 I20	I2 I9 I10	I2 I9 I10	
10	I1 I2 I5 I6 I7 I8 I9 I10 I11 I12 I13 I14 I16 I17 I18 I19 I20	I2 I9 I10	I2 I9 I10	
11	I1 I6 I8 I11 I12 I13 I14 I16 I17 I18 I19 I20	I2 I5 I7 I9 I10 I11 I12	I11 I12	
12	I1 I6 I8 I11 I12 I13 I14 I16 I17 I18 I19 I20	I2 I5 I7 I9 I10 I11 I12	I11 I12	
13	I1 I6 I8 I13 I14 I16 I17 I18 I19 I20	I1 I2 I5 I6 I7 I9 I10 I11 I12 I13 I14 I16 I17 I18 I19 I20	I1 I6 I13 I14 I16 I17 I18 I19 I20	

14	I1 I6 I8 I13 I14 I16 I17 I18 I19 I20	I1 I2 I5 I6 I7 I9 I10 I11 I12 I13 I14 I16 I17 I18 I19 I20	I1 I6 I13 I14 I16 I17 I18 I19 I20	
16	I1 I6 I8 I13 I14 I16 I17 I18 I19 I20	I1 I2 I5 I6 I7 I9 I10 I11 I12 I13 I14 I16 I17 I18 I19 I20	I1 I6 I13 I14 I16 I17 I18 I19 I20	
17	I1 I6 I8 I13 I14 I16 I17 I18 I19 I20	I1 I2 I5 I6 I7 I9 I10 I11 I12 I13 I14 I16 I17 I18 I19 I20	I1 I6 I13 I14 I16 I17 I18 I19 I20	
18	I1 I6 I8 I13 I14 I16 I17 I18 I19 I20	I1 I2 I5 I6 I7 I9 I10 I11 I12 I13 I14 I16 I17 I18 I19 I20	I1 I6 I13 I14 I16 I17 I18 I19 I20	
19	I1 I6 I8 I13 I14 I16 I17 I18 I19 I20	I1 I2 I5 I6 I7 I9 I10 I11 I12 I13 I14 I16 I17 I18 I19 I20	I1 I6 I13 I14 I16 I17 I18 I19 I20	
20	I1 I6 I8 I13 I14 I16 I17 I18 I19 I20	I1 I2 I5 I6 I7 I9 I10 I11 I12 I13 I14 I16 I17 I18 I19 I20	I1 I6 I13 I14 I16 I17 I18 I19 I20	

Table B.6: Third iteration

Indicator	Reachability set	Antecedent set	Intersection set	Iteration and level
1	I1 I6 I13 I14 I16 I17 I18 I19 I20	I1 I2 I5 I6 I7 I9 I10 I11 I12 I13 I14 I16 I17 I18 I19 I20	I1 I6 I13 I14 I16 I17 I18 I19 I20	***III***
2	I1 I2 I5 I6 I7 I9 I10 I11 I12 I13 I14 I16 I17 I18 I19 I20	I2 I9 I10	I2 I9 I10	
5	I1 I5 I6 I7 I11 I12 I13 I14 I16 I17 I18 I19 I20	I2 I5 I7 I9 I10	I5 I7	
6	I1 I6 I13 I14 I16 I17 I18 I19 I20	I1 I2 I5 I6 I7 I9 I10 I11 I12 I13 I14 I16 I17 I18 I19 I20	I1 I6 I13 I14 I16 I17 I18 I19 I20	***III***

7	I1 I5 I6 I7 I11 I12 I13 I14 I16 I17 I18 I19 I20	I2 I5 I7 I9 I10	I5 I7	
9	I1 I2 I5 I6 I7 I9 I10 I11 I12 I13 I14 I16 I17 I18 I19 I20	I2 I9 I10	I2 I9 I10	
10	I1 I2 I5 I6 I7 I9 I10 I11 I12 I13 I14 I16 I17 I18 I19 I20	I2 I9 I10	I2 I9 I10	
11	I1 I6 I11 I12 I13 I14 I16 I17 I18 I19 I20	I2 I5 I7 I9 I10 I11 I12	I11 I12	
12	I1 I6 I11 I12 I13 I14 I16 I17 I18 I19 I20	I2 I5 I7 I9 I10 I11 I12	I11 I12	
13	I1 I6 I13 I14 I16 I17 I18 I19 I20	I1 I2 I5 I6 I7 I9 I10 I11 I12 I13 I14 I16 I17 I18 I19 I20	I1 I6 I13 I14 I16 I17 I18 I19 I20	***III***
14	I1 I6 I13 I14 I16 I17 I18 I19 I20	I1 I2 I5 I6 I7 I9 I10 I11 I12 I13 I14 I16 I17 I18 I19 I20	I1 I6 I13 I14 I16 I17 I18 I19 I20	***III***
16	I1 I6 I13 I14 I16 I17 I18 I19 I20	I1 I2 I5 I6 I7 I9 I10 I11 I12 I13 I14 I16 I17 I18 I19 I20	I1 I6 I13 I14 I16 I17 I18 I19 I20	***III***
17	I1 I6 I13 I14 I16 I17 I18 I19 I20	I1 I2 I5 I6 I7 I9 I10 I11 I12 I13 I14 I16 I17 I18 I19 I20	I1 I6 I13 I14 I16 I17 I18 I19 I20	***III***
18	I1 I6 I13 I14 I16 I17 I18 I19 I20	I1 I2 I5 I6 I7 I9 I10 I11 I12 I13 I14 I16 I17 I18 I19 I20	I1 I6 I13 I14 I16 I17 I18 I19 I20	***III***
19	I1 I6 I13 I14 I16 I17 I18 I19 I20	I1 I2 I5 I6 I7 I9 I10 I11 I12 I13 I14 I16 I17 I18 I19 I20	I1 I6 I13 I14 I16 I17 I18 I19 I20	***III***
20	I1 I6 I13 I14 I16 I17 I18 I19 I20	I1 I2 I5 I6 I7 I9 I10 I11 I12 I13 I14 I16 I17 I18 I19 I20	I1 I6 I13 I14 I16 I17 I18 I19 I20	***III***

Table B.7: Fourth iteration

Indicator	Reachability set	Antecedent set	Intersection set	Iteration and level
2	I2 I5 I7 I9 I10 I11 I12	I2 I9 I10	I2 I9 I10	
5	I5 I7 I11 I12	I2 I5 I7 I9 I10	I5 I7	
7	I5 I7 I11 I12	I2 I5 I7 I9 I10	I5 I7	
9	I2 I5 I7 I9 I10 I11 I12	I2 I9 I10	I2 I9 I10	
10	I2 I5 I7 I9 I10 I11 I12	I2 I9 I10	I2 I9 I10	
11	I11 I12	I2 I5 I7 I9 I10 I11 I12	I11 I12	***IV***
12	I11 I12	I2 I5 I7 I9 I10 I11 I12	I11 I12	***IV***

Table B.8: Fifth iteration

Indicator	Reachability set	Antecedent set	Intersection set	Iteration and level
2	I2 I5 I7 I9 I10	I2 I9 I10	I2 I9 I10	
5	I5 I7	I2 I5 I7 I9 I10	I5 I7	***V***
7	I5 I7	I2 I5 I7 I9 I10	I5 I7	***V***
9	I2 I5 I7 I9 I10	I2 I9 I10	I2 I9 I10	
10	I2 I5 I7 I9 I10	I2 I9 I10	I2 I9 I10	

Table B.9: Sixth iteration

Indicator	Reachability set	Antecedent set	Intersection set	Iteration and level
2	I2 I5 I7 I9 I10	I2 I9 I10	I2 I9 I10	***VI***
9	I2 I5 I7 I9 I10	I2 I9 I10	I2 I9 I10	***VI***
10	I2 I5 I7 I9 I10	I2 I9 I10	I2 I9 I10	***VI***

Appendix C – Chapter 5

C.1 Input Data

The input data used in the model for the construction phase are presented in Table C.1. The technology partners responsible for the construction of the systems were requested to monitor and report all data reported in Table C.1.

Table C.1: Construction phase data obtained from the project partners

Component	Cost of unit incl. installation [€]	Required Built Material	Weight of materials [kg]	Transported materials	From	Machinery for construction works onsite	Values
UASB	270000	Stainless steel	4500	All materials	Barcelona, Spain	Big excavator (excavated soil; m3)	2500
		Fiberglass-reinforced polyester	500			Small excavator (excavated soil; m3)	1000.0
		Rubber	150			Rock drill excavator (working hours; h)	300
		PRFV	207.43			Bobcat (working hours; h)	200
CW	135757	Gravel (0.2-5 mm)	341354.16	Gravel	Limnos, Greece	Tillage ploughing (working area; m2)	9000
		Gravel (5-10 mm)	421061.3	Sand	Khalkidhiki, Greece		
		Gravel (10-20 mm)	37289	Polypropylene (non-woven geotextile)	Athens, Greece		
		Gravel (20-40 mm)	168820.24	HDPE liner	Heraklion, Crete, Greece		
		Gravel (30-50 mm)	318037.12	Biodegradable natural jute fibre (jute geotextile)	Kalloni, Lesvos, Greece		
		Sand	120460	Concrete & steel reinforcements (for HYDRO 1&2 in total)	Gavathas, Lesvos, Greece		
		Polypropylene (non-woven geotextile)	750.9	PVC pipes	Mytilene, Lesvos, Greece		

		HDPE carbon black liner	85.102	HDPE pipes	Mytilene, Lesvos, Greece	
		Biodegradable natural jute fibre (jute geotextile)	81.6			
		Concrete for all HYDRO 1&2 systems	312000			
		Steel reinforcements for all HYDRO 1&2 systems	8375			
		PVC pipes	2370.365			
		HDPE pipes	1856.113			
UF & UV	54800	Modified polyether sulfone (PESm) for membrane	105.776	All UF materials	Greifenberg, Germany	
		PVC	50	All UV materials	Ontario, Canada	
		Stainless steel (end cap)	35.796			
		Mercury	0.0008			
		Polypropylene	0.0922			
		Silica sand	0.338			
		Cable	0.06			
		Borosilicate (glass tube)	0.1			
CHP	40000	Steel	1500	All materials	Athens, Greece	
		PVC	680			
Composting	25000	Inox	300	All materials	Cheshire, UK	
		PVC	200			
AGF	15000	Stones	80580.6	Stones	Karistos, Greece	
		Excavated stones	4677.84	Drip irrigation	Thessaloniki, Greece	
		Polyethylene	2044			
Total Water Consumption during construction of HYDRO system [m^3]						448.4
Total Waste generated during construction of HYDRO system [kg]						50,000.00
Total land use of HYDRO1 [m^2]						1,131.00
Total land use of HYDRO2 [m^2]						9,500.00

The input data as well as the assumptions used in the model for the operation phase are presented in Table C.2. All input data (i.e. monitored data) were obtained from monitoring and sampling campaigns conducted between February 2021 – November 2021, unless otherwise stated. The reported min and max values are used as the investigated ranges of the variables in the sensitivity analysis.

Table C.2: Monitored data and assumptions used in the model

System Component	Parameter [units]	Value	Min Value	Max Value
Monitored Data				
Qualitative parameters (WW influent)	TN [mg/L]	70	60	80
	P [mg/L]	10	7.4	13.4
	COD [mg/L]	807	530	1053
	TSS [mg/L]	350	200	450
	BOD_5 [mg/L]	331		
	E. Coli [EC/100 mL]	1.00E+07		
	COD/TOC in influent WW	2.9		
Water flows	WW influent (winter) [m3/d]	30	10	30
	WW influent (summer) [m3/d]	80	80	100
Energy consumption	Energy use in pre-treatment [kWh/d]	0		
	Energy use in UASB (winter) [kWh/m3]	8.07	24.08 (for $10m^3/d$)	8.07 (for $30m^3/d$)
	Energy use in UASB (summer) [kWh/m3]	2.17	2.17 (for $10m^3/d$)	1.75 (for $30m^3/d$)
	Energy use in CW (summer & winter constant) [kWh/m3]	0.07		
	Energy use in UF (summer & winter constant) [kWh/m3]	0.008		
	Energy use in UV (summer & winter constant) [kWh/m3]	1.6		
	Energy use in Composting [kWh/t of sludge]	9		
	Energy use in CHP [kWh/m3]	2.4		
	Energy use in AGF (open channels) [kWh/d]	2		
	Energy use in AGF (drip irrigation) [kWh/d]	6		
	Energy consumption of existing WWTP [kWh/yr]	117600		
Pre-treatment waste	Waste from screening (winter) [kg/d]	4		
	Waste from screening (summer) [kg/d]	2		
	Waste from gritting (winter) [kg/d]	2		
	Waste from gritting (summer) [kg/d]	0.5		
	Waste from oil skimming (winter) [kg/d]	0.025		
	Waste from oil skimming (summer) [kg/d]	0.5		
UASB	Produced sludge in UASB [kg SS/m3]	0.025		
	COD removal in winter [% of the influent COD]	55%	45%	65%
	COD removal in summer [% of the influent COD]	72%	63%	82%
	TSS removal [%]	70%		
	Temperature (winter) [ºC]	15.00		
	Temperature (summer) [ºC]	22.00		
	Dissolved methane (winter) [mg/L]	22		
	Dissolved methane (summer) [mg/L]	20		
Vertical Flow (VF) Saturated (SAT) & Unsaturated (UNSAT) Constructed Wetlands	COD removal rate (winter)	93%	85%	95%
	COD removal rate (summer)	83%	73%	90%
	TN removal rate (winter)	45%	40%	60%
	TN removal rate (summer)	45%	40%	60%
	P removal rate (winter)	10%	10%	50%
	P removal rate (summer)	22%	14%	32%
	TSS removal rate [%]	94%		
	BOD_5/TOC in the effluent of CW	0.50		
	Area covered by Phragmites Australis [m2]	245		

	Area covered by Typha [m2]	120
	Area covered by Juncus Inflexus [m2]	120
	Area covered by Iris Pseudacorus [m2]	120
	Area covered by Scirpus Lacustris [m2]	120
	Area covered by Scirpus Albescent [m2]	120
UF & UV	UF Backwash requirement [% of the process influent]	6.68
	COD/BOD_5 in effluent WW	5
	Measured TSS in the effluent after UF [mg/L]	4
	NaClO [mg/L]	0.025
	HCl [mg/L]	0.525
	NaOH [mg/L]	0.95
Greek regulatory limits for **unrestricted** irrigation[1]	BOD_5 [mg/L]	10.00
	TSS [mg/L]	10.00
	TN [mg/L]	45.00
	E. Coli [EC/100 mL]	5.00
Greek regulatory limits for **restricted** irrigation[1]	BOD_5 [mg/L]	25.00
	TSS [mg/L]	35.00
	TN [mg/L]	45.00
	E. Coli [EC/100 mL]	200.00
Combined Heat and Power (CHP)	Monoethanoloamine solution (MEA/water) [%]	30%
	MEA solution removal capacity [m3 biogas/L]	0.15
	Scrubber volume [m3]	0.30
	Regeneration losses [m3/yr]	0.03
	Leaks [%]	5.00
Composting	Water input [m3/yr]	1.63
	Green waste (municipal) [kg/yr]	2800.00
	CO2 emitted [kg/yr]	1498.89
	NH3 emitted [kg/yr]	18.73
	Solid mass of produced compost [kg/yr]	1644.60
	Water content of produced compost [kg/yr]	1096.27
Economic data	Cost of UASB (unit incl. installation) [€]	270000
	Cost of CW (unit incl. installation) [€]	135757
	Cost of UF (unit incl. installation) [€]	50000
	Cost of UV (unit incl. installation) [€]	4800
	Cost of CHP (unit incl. installation) [€]	15000
	Cost of Composting (unit incl. installation) [€]	25000
	Cost of AGF (unit incl. installation) [€]	15000
	Government invest. Grant [%]	50%
	Loan interest rate [%]	1.5%
	Loan duration [years]	25
	Energy price [€/kWh]	0.11
	Water price for irrigation [€/m3]	0.2
	Water price for other uses (0-9 m3) [€/m3]	0.00
	Maintenance costs for UASB & CW [€/year]	4000
	Maintenance costs for UF & UV [€/year]	1250
	Maintenance costs for Composting [€/year]	800
	Maintenance costs for CHP [€/year]	1500
	Maintenance costs for AGF [€/year]	1000
	HR requirement (HYDRO 1&2) [€/year]	17100
	Compost selling price [€/tn]	140
	Wastewater treatment tax [€/m3]	2.5
	No of school visits [visits/yr]	5
	Price of school visit [€/visit]	50
	No of tourist visits [visits/yr]	100
	Price of tourist visit [€/visit]	15

Agroforestry (AGF)	Drip irrigation coverage as percentage of the total irrigated area	50%	0%	100%
	Open channels irrigation coverage as percentage of the total irrigated area	50%		
	Actual N requirements [kg/yr]	64.75		
	Compost requirements [kg/ha]	2000.00	1700	2000
	Total area of AGF [m2]	9500.00		
AGF (number of species)[2]	Arbutus Unedo	3	0	6
	Castanea	1	0	2
	Corylus Maxima	8	0	16
	Cydonia Oblonga	8	0	16
	Elaeagnus Multiflora	2	0	4
	Eriobotrya Japonica	2	0	4
	Ficus Carica	20	0	40
	Hippophae Rhamnoides	25	0	50
	Laurus Nobilis	33	0	66
	Lavandula Angustifolia	2962	0	5924
	Lycium Barbarum	174	0	348
	Malus	18	0	36
	Mentha Spicata	220	0	440
	Moringa	8	0	16
	Morus Nigra / Alba	1	0	2
	Myrtus Communis	210	0	420
	Olea Europea	16	0	32
	Avocado	2	0	4
	Pimpinella Anisum	1150	0	2300
	Prunus Avium	2	0	4
	Prunus Dulcis	16	0	32
	Punica Granatum (Pomegranate)	16	0	32
	Rubus Fruticosus	276	0	552
	Sideritis	55	0	110
	Origanum Vulgare	900	0	1800
	Satureja Thymbra	82	0	164
	Cistus Creticus	80	0	160
	Juniperus Communis	100	0	200
	Pelargonium Graveolens	57	0	114
	Rosmarinus Officinalis	94	0	188
	Melissa Officinalis	75	0	150
	Allium Schoenoprasum	126	0	252
	Basilikum	62	0	124
	Cicer Arietinum	84	0	168
	Citrullus Lanatus	71	0	142
	Cucurbita (moschata 'Butternut')	14	0	28
	Sorbaronia Mitschurinii	404	0	808
	Pear	2	0	4
	Quercus	2	0	4
	Calendula Officinalis	61	0	122
	Physalis Peruviana	86	0	172
	Rubus Ideaus	120	0	240
	Zea Mays	6200	0	12400
AGF (market value of products)[3]	Arbutus Unedo market price [€/kg]	1.2		
	Castanea [€/kg]	5	3	7
	Corylus Maxima[€/kg]	6	4	8
	Cydonia Oblonga [€/kg]	1.5	1	2
	Elaeagnus Multiflora [€/kg]	1.5		
	Eriobotrya Japonica [€/kg]	3	2	4
	Ficus Carica [€/kg]	6	4	8

	Hippophae Rhamnoides [€/kg]	6	5	7
	Laurus Nobilis [€/kg]	6		
	Lavandula Angustifolia [€/kg]	6.25	3.5	9
	Lycium Barbarum [€/kg]	12.5	11	14
	Malus [€/kg]	2	1.5	2.5
	Mentha Spicata [€/kg]	5.5	3	8
	Moringa [€/kg]	5.88		
	Morus Nigra / Alba [€/kg]	4.5	3	6
	Myrtus Communis [€/kg]	4		
	Olea Europea [€/kg]	2	1.2	2.8
	Avocado [€/kg]	3	2.5	3.5
	Pimpinella Anisum [€/kg]	11	8	14
	Prunus Avium [€/kg]	3	2	4
	Prunus Dulcis [€/kg]	2.25	1.5	3
	Punica Granatum (Pomegranate) [€/kg]	2.25	1.5	3
	Rubus Fruticosus [€/kg]	31	25	37
	Sideritis [€/kg]	6.5	5	8
	Origanum Vulgare [€/kg]	5.5	4	7
	Satureja Thymbra [€/kg]	5.5	4	7
	Cistus Creticus [€/kg]	5.5	4	7
	Juniperus Communis [€/kg]			
	Pelargonium Graveolens [€/kg]	5.5	4	7
	Rosmarinus Officinalis [€/kg]	5.5	4	7
	Melissa Officinalis [€/kg]	5.5	4	7
	Allium Schoenoprasum [€/kg]	5.5	4	7
	Basilikum [€/kg]	5.5	4	7
	Cicer Arietinum [€/kg]	5	3	7
	Citrullus Lanatus [€/kg]	1.1	0.7	1.5
	Cucurbita (moschata 'Butternut') [€/kg]	0.6	0.4	0.8
	Sorbaronia Mitschurinii [€/kg]	7	6	8
	Pear [€/kg]	2	1.5	2.5
	Quercus [€/kg]			
	Calendula Officinalis [€/kg]	5.5	4	7
	Physalis Peruviana [€/kg]	1.5	1	2
	Rubus Ideaus [€/kg]	7	4	10
	Zea Mays [€/kg]	1.5	1	2
Climatological data of the area[4]	Mean T in Jan [ºC]	9.5	3.65	15.23
	Mean T in Feb [ºC]	10.2	4.00	17.24
	Mean T in Mar [ºC]	12.5	5.75	20.05
	Mean T in Apr [ºC]	16.3	8.06	23.77
	Mean T in May [ºC]	21.3	13.51	27.75
	Mean T in Jun [ºC]	26.0	18.79	32.29
	Mean T in Jul [ºC]	28.1	20.78	34.5
	Mean T in Aug [ºC]	27.9	20.81	35.1
	Mean T in Sep [ºC]	24.0	16.65	30.85
	Mean T in Oct [ºC]	19.2	13.01	25.59
	Mean T in Nov [ºC]	14.6	8.07	21.23
	Mean T in Dec [ºC]	11.1	5.19	16.77
	Mean P in Jan [mm]	114.2	55.4	167.6
	Mean P in Feb [mm]	109.1	34.4	295.6
	Mean P in Mar [mm]	53.3	17	116.8
	Mean P in Apr [mm]	36.2	0	133.2
	Mean P in May [mm]	25.9	4.2	74.8
	Mean P in Jun [mm]	18.8	0.2	44.8
	Mean P in Jul [mm]	0.3	0	1.6
	Mean P in Aug [mm]	1.9	0	11

	Mean P in Sep [mm]	21.7	0.8	66.4
	Mean P in Oct [mm]	56.4	5.8	136.2
	Mean P in Nov [mm]	71.9	0.8	195.2
	Mean P in Dec [mm]	86.5	0	177.4
	Percentage of day hours in Jan	6.8		
	Percentage of day hours in Feb	6.8		
	Percentage of day hours in Mar	8.3		
	Percentage of day hours in Apr	8.9		
	Percentage of day hours in May	10.0		
	Percentage of day hours in Jun	10.0		
	Percentage of day hours in Jul	10.2		
	Percentage of day hours in Aug	9.5		
	Percentage of day hours in Sep	8.4		
	Percentage of day hours in Oct	7.8		
	Percentage of day hours in Nov	6.8		
	Percentage of day hours in Dec	6.5		
	Assumptions			
System Component	**Parameter [units]**	**Value**	**Min Value**	**Max Value**
UASB[5]	P content in sludge [% of the produced sludge in kg SS]	1		
	Solids in produced sludge [%]	3		
	VSS in sludge [%]	75		
	VSS/COD	1.8		
	Methane produced per COD removed [m3/kg]	0.35		
	Methane content of biogas [%]	60.00		
	N content of biogas [%]	0.20		
	System's efficiency for dissolved methane recovery [%]	40		
Constructed Wetlands[6]	Biomass density of Phragmites Australis [g/m^2]	1901	558	3244
	Biomass density of Typha [g/m^2]	1587	687	2487
	Biomass density of Juncus Inflexus [g/m^2]	1110.9	410.9	1810.9
	Biomass density of Iris Pseudacorus [g/m^2]	1110.9	410.9	1810.9
	Biomass density of Scirpus Lacustris [g/m^2]	1110.9	410.9	1810.9
	Biomass density of Scirpus Albescent [g/m^2]	1110.9	410.9	1810.9
CHP[7]	Efficiency of electricity production [%]	35.00		
	Efficiency of thermal energy production [%]	50.00		
	Calorific value of biogas [kcal/m3]	5500.00		
Composting[8]	C content of produced compost [% of solid mass]	35.00		
	N content of produced compost [% of solid mass]	3.00		
	P content of produced compost [% of solid mass]	1.00		
AGF[9]	Efficiency coefficient drip	0.90		
	Efficiency coefficient open channels	0.65		
	Efficiency coefficient of the distribution network	0.65		
	Green waste generated [kg/yr]	0		
	Indicative area occupied from trees [m2]	2.25		
	Indicative area occupied from shrubs [m2]	0.34		
AGF (expected yield)[9]	Arbutus Unedo literature yield [kg/tree]	5	2	8
	Castanea [kg/tree/yr]	50	20	80
	Corylus Maxima [kg dry weight tree/yr]	7.00	4	10
	Cydonia Oblonga [kg/tree]	50	20	80
	Elaeagnus Multiflora [kg/tree]	12	10	15
	Eriobotrya Japonica [kg/tree/yr]	40	20	60

	Ficus Carica [kg fresh/tree/yr]	55	40	70
	Hippophae Rhamnoides [kg/tree]	3.5	1	7
	Laurus Nobilis [kg fresh leaf/tree]	1.5	1	2
	Lavandula Angustifolia [kg/acre]	275	150	400
	Lycium Barbarum [kg/tree] (Oguz & Erdogan, 2016)	0.3	0.2	0.4
	Malus [kg/tree/yr]	40	20	60
	Mentha Spicata [kg/acre]	400	200	600
	Moringa [ton/acre] (3rd yr)	0.7		
	Morus Nigra / Alba [kg/tree/yr]	22.5	15	30
	Myrtus Communis [kg/tree] (Mulas et al., 2001)	1.25	1	1.5
	Olea Europea [kg/tree/yr]	45	20	70
	Avocado [kg/tree/yr]	55	30	80
	Pimpinella Anisum [kg dry weight/yr]	0.1	0.08	0.12
	Prunus Avium [kg/tree/yr]	30	20	40
	Prunus Dulcis [kg/tree/yr]	35	20	50
	Punica Granatum (Pomegranate) [kg/tree] third year	25	20	30
	Rubus Fruticosus [kg/plant]	3	2	4
	Sideritis [kg dry weight/ha] (Dordas, 2012)	900	600	1200
	Origanum Vulgare [kg/acre]	100	80	120
	Satureja Thymbra [kg/ha]	55	40	70
	Cistus Creticus [kg of leaves/plant/yr]	12.5	10	15
	Juniperus Communis [kg/ha] (low yield)	2250		
	Pelargonium Graveolens [ton/ha/yr]	1.15	0.8	1.3
	Rosmarinus Officinalis (maximum fresh leaf yield) [kg/ha]	1650	1800	2500
	Melissa Officinalis [tonnes/ ha]	5	4	6
	Allium Schoenoprasum [kg/m2]	1.5	1	2
	Basilikum [t/ha]	0.6	0.4	0.8
	Cicer Arietinum [kg/ha]	1150	1000	1300
	Citrullus Lanatus [t/ha]	35	30	40
	Cucurbita (moschata 'Butternut') [t/ha]	20	15	25
	Sorbaronia Mitschurinii [kg/acre]	1400	1200	1600
	Pear [kg/tree]	45	30	60
	Quercus			
	Calendula Officinalis [kg/ha]	20037		
	Physalis Peruviana [t/ha]	3	2.5	3.5
	Rubus Ideaus [t/ha]	3	2	4
	Zea Mays [kg/plant]	0.2	0.15	0.25
	kc of Arbutus Unedo (Jan – Dec)	0.6		
	kc of Castanea (Jan – Mar & Oct – Dec)	0.6		
	kc of Castanea (Apr)	1.0		
	kc of Castanea (May – Sep)	1.2		
	kc of Castanea (Jun – Aug)	1.3		
	kc of Corylus Maxima (Jan – Dec)	0.6		
	kc of Cydonia Oblonga (Jan – Dec)	0.6		
Kc values of the different species[9]	kc of Elaeagnus Multiflora (Jan – Dec)	0.6		
	kc of Eriobotrya Japonica (Jan – Dec)	0.6		
	kc of Ficus Carica (Jan – Apr & Oct – Dec)	0.5		
	kc of Ficus Carica (May)	0.6		
	kc of Ficus Carica (Jun – Sep)	0.7		
	kc of Hippophae Rhamnoides (Jan – Dec)	0.6		
	kc of Laurus Nobilis (Jan – Dec)	0.6		
	kc of Lavandula Angustifolia (Jan – Dec)	0.6		
	kc of Lycium Barbarum (Jan – Dec)	0.6		

kc of Malus (Jan – Mar & Oct – Dec)	0.6
kc of Malus (Apr)	1.0
kc of Malus (May & Sep)	1.2
kc of Malus (Jun – Aug)	1.3
kc of Mentha Spicata (Jan – Dec)	0.6
kc of Moringa (Jan – Dec)	0.6
kc of Morus Nigra / Alba (Jan – May & Oct – Dec)	0.3
kc of Morus Nigra / Alba (Jun – Sep)	1.1
kc of Myrtus Communis (Jan – Dec)	0.6
kc of Olea Europea (Jan – May & Sep – Dec)	0.3
kc of Olea Europea (Jun)	0.4
kc of Olea Europea (Jul – Jul)	0.5
kc of Avocado (Jan – Dec)	0.6
kc of Pimpinella Anisum (Jan – Dec)	0.6
kc of Prunus Avium (Jan – Mar & Oct – Dec)	0.6
kc of Prunus Avium (Apr)	1.0
kc of Prunus Avium (May & Sep)	1.2
kc of Prunus Avium (Jun – Aug)	1.3
kc of Prunus Dulcis (Jan – May & Oct - Dec)	0.4
kc of Prunus Dulcis (Jun – Aug)	0.9
kc of Prunus Dulcis (Sep)	0.7
kc of Pomegranate (Jan – Dec)	0.6
kc of Rubus Fruticosus (Jan – Dec)	0.6
kc of Sideritis (Jan – Dec)	0.6
kc of Origanum Vulgare (Jan – Dec)	0.6
kc of Satureja Thymbra (Jan – Dec)	0.6
kc of Cistus Creticus (Jan – Dec)	0.6
kc of Juniperus Communis (Jan – Dec)	0.6
kc of Pelargonium Graveolens (Jan – Dec)	0.6
kc of Rosmarinus Officinalis (Jan – Dec)	0.6
kc of Melissa Officinalis (Jan – Dec)	0.6
kc of Allium Schoenoprasum (Jan – Dec)	0.6
kc of Basilikum (Jan – Dec)	0.6
kc of Cicer Arietinum (Jan – Dec)	0.6
kc of Citrullus Lanatus (Jan – Dec)	0.6
kc of Cucurbita (Jan – Dec)	0.6
kc of Sorbaronia Mitschurinii (Jan – Dec)	0.6
kc of Pear (Jan – Mar & Oct – Dec)	0.6
kc of Pear (Apr)	1.0
kc of Pear (May – Sep)	1.2
kc of Pear (Jun – Aug)	1.3
kc of Quercus (Jan – Mar & Oct – Dec)	0.6
kc of Quercus (Apr)	1.0
kc of Quercus (May & Sep)	1.2
kc of Quercus (Jun – Aug)	1.3
kc of Calendula Officinalis (Jan – Dec)	0.6
kc of Physalis Peruviana (Jan – Dec)	0.6
kc of Rubus Ideaus (Jan – Dec)	0.6
kc of Zea Mays (Jan – Apr & Sep – Dec)	0.3
kc of Zea Mays (May – Jul)	1.2
kc of Zea Mays (Aug)	0.6

[1] Υ.Α. οικ. 145116/2011 (ΦΕΚ 354/Β`8.3.2011)

[2] number of planted species, min values indicate an assumption that the species will not survive, max values indicate an assumption that the number of species will be doubled

[3] market value of products based on a survey conducted to the local markets

[4] average, min and max values considering reported local climatological data for a 28 years period (1990-2018)

[5]https://www.hydrousa.org/wp-content/uploads/2020/12/HYDROUSA-Design-of-the-UASB-and-biogas-upgrade.pdf

[6] Avellán and Gremillion, 2019

[7] Martens, 1998

[8] HYDROUSA deliverable D3.7

9 HYDROUSA deliverable D4.3

C.2 Modelling Description of System Components

Natural system component:

For the estimation of the water needs in the semi-natural component of the system (i.e. agroforestry), for each average monthly temperature value, the corresponding reference evapotranspiration for each plant species is calculated using the empirical Blaney-Criddle method:

$$PET_c = k_c \; x \; f \tag{C.1}$$

$$f = \frac{(32 + 1.8 \; x \; T_a)}{3.94} \; x \; p \tag{C.2}$$

Where, PET_c [mm/month] is the potential evapotranspiration; k_c is the crop coefficient for each month; f [mm/month] is the climatic factor; T_a [^oC] is the mean air temperature of the month; p is the average daily percentage of total annual duration of day hours as a function of month and latitude.

The same equations – i.e. Eq. (C.1) and (C.2) – are used to calculate the evapotranspiration in the constructed wetlands, during the summer months. The k_c value used is 2.43, obtained from Papaevangelou et al. (2012).

To calculate the net water needs, the effective precipitation is calculated as follows:

$$P_e = P \; x \; 80\% \tag{C.3}$$

Where, P_e is the effective precipitation; and P [mm/month] is the monthly precipitation.

The water demand to meet the requirements of each crop is calculated as follows:

$$Q_{w,i} = (PET_c - P_e)\ x\ A_i\ x\ 0.001 \quad , \qquad for\ PET_c > P_e \tag{C.4}$$

$$Q_{w,i} = 0 \quad , \qquad for\ PET_c < P_e \tag{C.5}$$

Where, $Q_{w,I}$ [m^3/month] is the monthly water demand for I plant species; and A_i [m^2] is the indicative area occupied by I plant species.

The total water requirements ($Q_{w,T}$) of the agroforestry area are calculated by summing up all the $Q_{w,I}$ of each plant species.

The irrigation requirements of the agroforestry depend on the water losses of the system due to the irrigation method that is used. Therefore, the irrigation requirements ($Q_{ir,T}$) are calculated by considering the distribution efficiency (E_d) and application efficiency (E_f) of the implemented irrigation methods, as follows:

$$Q_{ir,T} = \frac{(Q_{w,T}\ x\ C_{m,i})/E_{f,i}}{E_{d,i}} + \frac{(Q_{w,T}\ x\ C_{m,j})/E_{f,j}}{E_{d,j}} \tag{C.6}$$

Where, $C_{m,I}$ [%] is the percentage of the agroforestry area that is irrigated with irrigation method I and $C_{ir,j}$ [%] is the percentage of the agroforestry area that is irrigated with irrigation method j.

In this study, 2 irrigation methods are applied, i.e. drip irrigation and open channels irrigation. In Scenario 0, both irrigation methods are applied to half of the irrigated area (i.e. 50%), respectively. The percentages of the irrigation methods change in the different investigated scenarios.

Nodes of intersection:

The calculated $Q_{ir,T}$ is one of the controlling parameters that is used in the node of intersection between the wastewater treatment (HYDRO1) and the agroforestry (HYDRO2). Other controlling parameters that are used in the node of intersection are the effluent concentrations of BOD_5, TSS, TN and E.coli that are required to meet the Greek regulatory limits for unrestricted irrigation. If functions are developed in the nodes of intersection to test whether or not the regulatory requirements and the irrigation requirements of the agroforestry are met by the reclaimed wastewater. In case that the $Q_{ir,T}$ is more compared to the total volume of the reclaimed wastewater, the model is forced to use water from conventional water sources in order to meet the remaining requirement. In case that the Greek regulatory limits for unrestricted irrigation are not met, the model is again forced to use water for conventional sources. In case that water for conventional sources is used in HYDRO1, mineral fertilizer is applied to meet the nitrogen requirements of the field.

Anthropogenic system component:

The modelling simulation of HYDRO1 starts after the pretreatment, with the volume of influent wastewater entering UASB. The simulation is performed at a seasonal level (i.e. differentiating between summer and winter values) and then aggregation is performed to estimate the annual values that are required for the indicators.

The UASB process is mathematically described in the model, following the principles of the process as described in the work of de Lemos Chernicharo (2007). The modelling output of this process includes:

- the volume of produced biogas that goes to the CHP process, as well as the volume and mass of the CO_2 and CH_4 incorporated in the produced biogas;
- the volume of wastewater that goes to the CW, the TSS concentration, as well as the mass of COD, TOC, TN and P incorporated in the effluent wastewater;
- the volume and composition of produced sludge that after dewatering goes to the composting unit, as well as the mass of COD, TOC, TN and P incorporated in the produced sludge.

The CW process is modelled considering the removal efficiencies and the estimated evapotranspiration. This process calculates the volume of effluent wastewater, the TSS and BOD_5 concentrations, as well as the masses of COD, TOC, TN and P. The calculated concentrations of TSS and BOD_5 are compared to the Greek regulatory limits for unrestricted irrigation to test whether or not the UF process can be bypassed.

If the UF process cannot be bypassed, the model forces the CW effluent to enter the UF process in which, the TSS concentration is reduced at 4 mg/L and the COD concentration is reduced by 6 mg/L based on data obtained from sampling campaigns conducted onsite. This process further estimates the volume of effluent wastewater that is required for backwash, the volume of effluent wastewater that goes to the UV process, as well as the masses of COD, TOC, TN and P that are incorporated in backwash and effluent wastewater that goes to UV. The amount of chemicals required in this process are estimated as well. If the UF process can be bypassed, the model forces the CW effluent to enter directly the UV process.

In the UV process, the model forces the E.coli to reach the value of 4 EC/100 ml. All the effluent volumes and masses are the same as the influent values to the process, and the total effluent concentrations of COD, TSS, TOC, TN, P, and BOD_5 are estimated. The modelling output of the UV process enters the node of intersection to perform the required quantitative and qualitative checks as already described. In the developed model, the user can decide whether the remaining treated wastewater that meets the Greek regulatory limits for unrestricted irrigation is further valorized (i.e. sold to other users outside the system boundaries) or discharged at the water body.

The CHP process is simulated in the model using the produced biogas in UASB, its calorific value and the efficiencies of electricity and thermal production in order to estimate the thermal and electrical energy produced onsite. In the CHP process, calculations to estimate the requirement of MEA are performed. By considering the scrubber volume and the MEA solution removal capacity, the volume of processed biogas in order to start the regeneration of MEA is estimated. Considering the total volume of biogas per year, the number of regenerations and the regeneration losses of the solution per year are then estimated. Considering the regeneration losses, the number of regenerations per year and the scrubber volume, the volume of regenerated solution, of regenerated MEA and of MEA losses are estimated. Finally, the total amount of new MEA required in CHP is estimated.

The composting unit is simulated using the total amount of sludge produced in the UASB per year (388.75 kg TSS/year), assuming that the produced sludge is 3% solids the total mass of produced sludge is 12,598.33 kg/yr. The produced sludge is fed to a sludge drying reedbed unit to dewater the sludge to 10% solids and by assuming that a 10% of kg TSS will be lost during that process, an output of 3,498.80 kg of dewatered sludge/year enters the composting unit. The addition of green biomass (sawdust, wood chips and olive leaves) is needed to be mixed with the dewatered sludge as a bulking agent for the compost process. Table C.3 summarizes the characteristics of the dewatered sludge and the green biomass used in the model.

Table C.3: Characteristics of sludge and green biomass

Material	Molecular formula	Humidity [%]	Biodegradable [%]	Relative density
Organic sludge	$C_{61}H_{6}O_{29}N_{4}$	90	60	0.9
Inorganic sludge		90	0	0.9
Sawdust	$C_{6}H_{10}O_{4}$	15	20	0.2
Olive leaves	$C_{34}H_{60}O_{24}N$	30	40	0.4
Wood chips	$C_{295}H_{420}O_{186}N$	30	21.6	0.45

The molecular formula of sludge ang green biomass is used to estimate the molecular weight, the percentages of C, H, O and N, and the masses of C and N in the mixture. Different amounts of green biomass are tested in order to achieve a moisture content of 62-65% and C/N = 32-35 of the mixture in the composting unit. Based on the molecular weight, the molecular formula and the biodegradable component, the CO_2 and NH_3 emissions of the process are estimated as well. A water balance is developed considering the aeration process in the composting unit in order to estimate the additional water requirement of the process. At the output of the process, the total produced compost is estimated. From this total output, 1,700-2,000 kg/ha are applied annually to the agroforestry field, while the remaining compost is assumed to be disposed and not further valorized.

For all the incorporated processes, the model further estimates all system's emissions in terms of CH_4, CO_2 and N_2O in order to calculate both the fugitive emissions of the system – expressed as kg of CO_2 equivalents per year – and the masses of emissions – expressed as kg of C, N and P per year. The P emissions include only solid and liquid emissions.

After the simulation of each process as explained above, mass balance checks in terms of water, COD, carbon I, nitrogen (N) and phosphorus (P) is performed within the model. The model then summarizes the results of the resource flows by differentiating between different sources of inputs and different fate of outputs. Table C.4 presents the different categories of sources and fate of the resource flows, as well as the modelling results for Scenario 0.

Table C.4: Aggregation of resource flows in the model

Differentiation	Water Flows	Value [m^3/year]
Sources (input)	Water input to system (if linear)	26408.34
	Actual water input to system	20329.85
	Unavoided water input to system	15550.00
	Actual water requirements for system's operation	10858.34
	Water requirements met by conventional anthropogenic flows	4.23
	Water requirements met by natural flows	4775.61
	Water requirements met by anthropogenic recirculated flows	6078.49
Fate (output)	Discharged water	8946.50
	Internal recycled water	6078.49
	External recycled water	0.00
	Water consumed/used in the anthropogenic system	14.59
	Stored water in anthropogenic system	0.21
	Water losses in anthropogenic system	2.39
	Effectively utilized water in natural system (PET & infiltration)	6792.30
	Additional PET in CW	533.60
	Water losses in natural system	4040.26
Differentiation	**Carbon, Nitrogen, Phosphorus Flows**	**Value [kg/year]**
Sources (input)	C, N, P managed in the system	8310.41; 1441.59; 230.83
	Actual C, N, P input to system	5112.92; 1134.48; 168.06
	Unavoided C, N, P input	4342.16; 1101.69; 155.50
	C, N, P required for system's operation	3968.25; 339.90; 75.33
	Non-renewable C, N, P input	0.00; 0.00; 0.00
	C, N, P from external recycle	5112.92; 1134.48; 168.06
	C, N, P from internal recycle	3197.49; 307.11; 62.77
Fate (output)	C, N, P as waste	317.82; 545.18; 110.73
	C, N, P as emission	3575.77; 17.51; 0.00
	C, N, P sent to external recycle	0.00; 0.00; 0.00
	C, N, P sent to internal recycle	3197.49; 307.11; 62.77
	C, N, P consumed	1219.34; 571.79; 57.33

The energy consumption of all incorporated processes is estimated based on the data in Table C.2, in which the energy use is given as a function of influent/input (i.e. volume of wastewater, of biogas and mass of sludge). The energy use in agroforestry for the 2 irrigation methods is given in kWh/d, considering 188 days of irrigation.

In the economic section of the model, the cost of electricity, of water use, the maintenance costs and the human resources operation costs are estimated in order to further calculate the annual OPEX of the system. Additionally, system's revenues, savings and lost revenues are estimated. The economic calculations resulted in the following treatment and production costs for Scenario 0 (Table C.5).

Table C.5: Economic results of the model regarding production and treatment costs

Production & treatment costs	Value
WW treatment cost [€/m³]	1.59
Sludge treatment cost [€/kg SS]	10.89
Biogas treatment cost [€/m³]	1.22
Irrigation water production cost [€/m³]	1.61
Compost production cost [€/kg]	3.55
Energy production cost [€/kWh]	0.35
AGF products production cost [€/kg]	1.09

The mass balance and resource flows of the integrated system as produced with the developed model for Scenario 0 can be seen in Figure C.1.

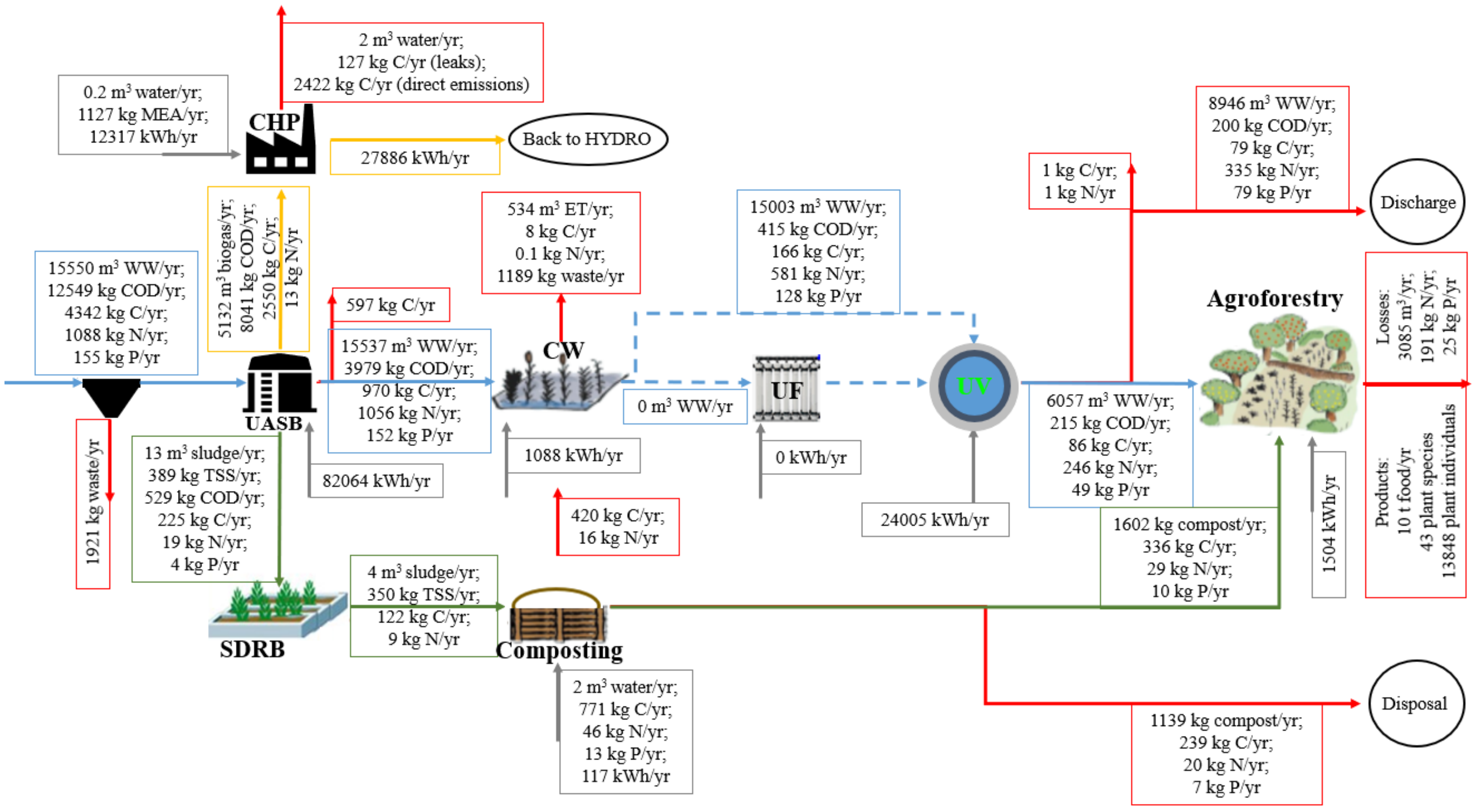

Figure C.1: Modelling calculations for Scenario 0

C.3 Selected Indicators

C.3.1 Construction Phase Circularity Performance Indicators

C.3.1.1 Land-related Indicators

The first indicators that are estimated for the construction phase of the HYDRO system are the land-related indicators.

The total land use of the HYDRO system is 10,631.00 m^2. The following three indicators (equations C.7-C.9) are related to land recycling:

$$LD\ [\%] = \frac{Land\ development\ making\ use\ of\ existing\ infrastracture}{Total\ land\ use} x\ 100 \tag{C.7}$$

Where, LD is the land densification.

In this study, the land development of the HYDRO system uses existing infrastructure.

$$GRLR\ [\%] = \frac{Land\ internally\ converted\ between\ grey\ land\ cover\ types}{Total\ land\ use} x\ 100 \tag{C.8}$$

Where, GRLR is the grey land recycling.

In this study, the area of the land occupied by HYDRO1 components apart from the land occupied from the CW represent the land that is internally converted between grey land cover types. The GRLR coincides in this study with the soil sealing of the HYDRO system.

$$GNLR\ [\%] = \frac{Land\ converted\ from\ grey\ to\ green\ land\ cover\ types}{Total\ land\ use} x\ 100 \tag{C.9}$$

Where, GNLR is the green land recycling.

In this study, the area of land occupied by CW and HYDRO2 represent the land that is converted from grey to green land cover types.

All the remaining indicators of the construction phase of the system are normalized using the total land use of the system.

C.3.1.2 Carbon Footprint & LCA-based Indicators

The Carbon Footprint (CF) of the construction phase of the system (i.e. embodied CF) is estimated based on the following equations:

$$CF_M = \sum_{i=1}^{n} M_i \ x \ EF_i \qquad (C.10)$$

$$CF_{RM} = \sum_{i=1}^{n} RM_i \ x \ EF_i \qquad (C.11)$$

$$CF_T = \sum_{i=1}^{n} tkm_i \ x \ d_i \ x \ EF_i \qquad (C.12)$$

$$CF_{CW} = \sum_{i=1}^{n} CW_i \ x \ EF_i \qquad (C.13)$$

$$CF_E = CF_M + CF_T + CF_{CW} - CF_{RM} \qquad (C.14)$$

$$CF_{E\_FU} = \frac{CF_E}{Total\ land\ use\ in\ m^2\ or\ lifetime\ of\ system\ in\ years} \qquad (C.15)$$

Where, M_i represents the amount of each built material that is used to build the system; RM_i represents the amount of the reused/repurposed materials that are used to build the system; tkm_i represents the tone-kilometer of transportation; d_i is the distance in km; CW_i represents the construction work that is performed on site in order to build the systems; and EF_i represents the corresponding emission factors for the conversion to kg of CO_2 equivalents.

C.3.1.3 Materials-related Indicators

In this indicator category, a differentiation is made between amount of renewable and non-renewable built materials, as well as between the amount of new, recycled, and reused/repurposed built materials. The results are presented in the Table C.6, both as actual values and as percentages to the total amount of the built materials used.

Table C.6: Materials-related indicators for the construction phase

Indicator	Value in kg	% of the total built materials	Value in kg/m^2 of land use
Non-renewable materials intensity (NRNMI)	1,827,991.33	100.00	171.95
Renewable materials intensity (RNMI)	81.60	0.00	0.01
New materials intensity (NMI)	1,823,395.09	99.74	171.52
Recycled materials intensity (RMI)	0.00	0.00	0.00
Reused/Repurposed materials intensity (RUMI)	4,677.84	0.26	0.44
Total built materials	1,828,072.93		171.96

C.3.1.4 Water-related Indicators

The water intensity to build the HYDRO system is estimated at 0.04 m^3/m^2 of land used. No renewable water sources are used.

C.3.1.5 Waste-related Indicators

The waste generation during building of the HYDRO system is estimated at 4.70 kg/m^2 of land used. All the generated waste is disposed to the local landfill.

C.3.1.6 Economic Indicators

The annual CAPEX ($CAPEX_A$) of the system is estimated based on the following equation:

$$\mathrm{CAPEX_A} = \mathrm{CAPEX_T} \text{ x } \frac{\mathrm{r \text{ x } (1+r)^N}}{\mathrm{(1+r)^N - 1}} \qquad \text{(C.16)}$$

Where, $CAPEX_T$ is the total cost of the system, considering the cost of each system's component including installation; r represents the loan interest rate [%]; and N represents the loan duration [years].

C.3.1.7 Results of Construction Phase Indicators

Table C.7 summarizes the modelling results in terms of indicators for the construction phase of the HYDRO system.

Table C.7: Construction phase indicator results

Indicator Category	Indicator	Actual value	Percentage [%]	Functional value [unit of actual value/m^2 of land]
Resource inflows, outflows, total	Non-renewable materials intensity	1,827,991 kg	100 %	171.95
	Renewable materials intensity	82 kg	0 %	0.01
	New materials	1,823,395 kg	99.74 %	171.51
	Recycled materials	0 kg	0 %	0
	Reused/Repurposed materials	4,678 kg	0.26 %	0.44
Water	Water from the mains	448 m^3	100 %	0.04
	Alternative water source	0 m^3	0 %	0
Energy	Non-renewable energy sources	-	100 %	-
	Renewable energy sources	-	0 %	-
Waste and Emissions	Remaining waste	50,000 kg	100 %	4.70
	Utilized waste	0 kg	0 %	0
	CF of built materials	125,341 kg of CO_2 equivalents	73.49 %	11.79
	CF of transportation	31,286 kg of CO_2 equivalents	18.34 %	2.94
	CF of construction works	13,925 kg of CO_2 equivalents	8.16 %	1.31
	Saved CF of reused built materials	84 kg of CO_2 equivalents	0.05 %	0.01
	Total CF of construction phase	170,552 kg of CO_2 equivalents	100 %	16.04
Economic	CAPEX	540,557 €	-	50.85
	Yearly CAPEX	31,485 €/yr	-	2.96
Other	System's Land Use	10,631 m^2	100 %	-
	Soil sealing	286 m^2	2.69 %	0.03
	Green land recycling	10,345 m^2	97.3 %	0.97
	Grey land recycling	286 m^2	2.69 %	0.03
	Land Densification	1,131 m^2	10.64 %	0.11

C.3.2 Operation Phase Circularity Performance Indicators

C.3.2.1 Water Indicators

Circular Water Inflow (CWI):

$$CWI = 1 - \frac{CAWF_T}{WRSO_T} \tag{C.17}$$

Where, $CAWF_T$ is the total volume of conventional anthropogenic water flows that enter the system to meet its water demand; and $WRSO_T$ is the total volume of water that is required for the system's operation.

In equation (1), there is a difference between the total volume of water input (WI_T) and the total volume of water that is required for the system's operation ($WRSO_T$). Since in any WWTP the volume of WW influent is unavoidable and it would always come from the same source (i.e. already used municipal or industrial water), the volume of influent WW is not considered neither in the $WRSO_T$ nor in the $CAWF_T$.

Circular Water Outflow (CWO):

$$CWO = 1 - \frac{DW + LW}{WO_T} \tag{C.18}$$

Where, DW is the volume of treated wastewater that is discharged; LW is the volume of water losses that occur in the system (both in anthropogenic and in nature-managed components); and WO_T is the total volume of water output (i.e. the volume of water that would leave the system if no circularity actions were taken).

Treated wastewater that is being discharged is considered as a non-circular water flow because the water recipient in this case is the sea, therefore this volume of water is lost from the freshwater resources of the area. Whether or not treated wastewater that is being discharged should be considered as a linear or circular water flow is case specific and depends on its quality, on the water scarcity and water balance of the catchment, and on the system boundaries that are considered.

Circular Water Flow (CWF):

$$CWF = \frac{2 - \left(\frac{CAWF_T}{WRSO_T} + \frac{DW + LW}{WO_T}\right)}{2} \tag{C.19}$$

Water Withdrawal Reduction (WWR):

$$WWR = \frac{WW_0 - WW_1}{WW_0} \tag{C.20}$$

Where, WW_0 is the volume of water that would be withdrawn from freshwater resources if no circularity actions were taken, or the volume of water that is withdrawn from freshwater resources during the first year of system's operation; and WW_1 is the volume of water that is actually withdrawn from freshwater resources in the investigated system.

In conventional systems at micro and meso scales, where the water balance of the catchment is difficult to be determined, WW_0 represents the volume of input water that comes from freshwater resources and is being used to meet the water requirements of the system, considering also the volume of water that is either not returned to the catchment or could potentially be returned to the catchment with a reduced quality. In these scales, water that is effectively returned to freshwater resources (WR) within the system's boundaries should be considered, as it is shown in the following equation:

$$WW_1 = WW - WR \tag{C.21}$$

Therefore, WWR indicator can have a negative value if WW_1 is greater than WW_0, a positive value if WW_1 is less than WW_0, and greater than 1 if WW_1 has a negative value indicating that the system returns more water to freshwater resources than it actually withdraws.

Water Demand Minimization (WDM):

$$WDM = \frac{WD_0 - WD_1}{WD_0} \tag{C.22}$$

Where, WD_0 represents the water demand of a baseline scenario (i.e. the scenario that the investigated system is compared to); and WD_1 is the new water demand of the investigated system.

In this study, the baseline scenario considers the volume of water that is required for UF backwash, for the CHP unit and the compost unit, the actual water needs of the AGF, and the irrigation requirements of the AGF considering the losses of the irrigation system, which consists of both open channels and drip irrigation. In the baseline scenario, open channels and drip irrigation contributes equally to the actual water needs of the AGF (i.e. 50% of the actual water needs are met with open channels, and 50% with drip irrigation). Since water demand for the CHP and the compost unit are stable, only the use of UF and changes in the operation of the irrigation system (i.e. unequal contribution of open channels and drip irrigation to the actual water needs) can have an impact on this indicator. Additionally, since natural feedback loops are not considered in this study, the actual water needs of the AGF are the same in both WD_0 and WD_1.

System's Water Efficiency for operation (SWE_{op}):

$$SWE_{op} = \frac{WRSO_T - LW_A - LW_N}{WRSO_T} \tag{C.23}$$

Where, LW_A represents the water losses in the anthropogenic component; and LW_N represents the water losses in the nature-managed component.

In this study, LW_A represents the water losses in the CHP unit and LW_N represents the runoff generated in the AGF.

Natural Hydrological Performance (NHP):

$$NHP = \frac{LW_N}{EUW_{PET+I}} \tag{C.24}$$

Where, EUW_{PET+I} represents the volume of water that is effectively utilized in the nature-managed component, considering the generated evapotranspiration and infiltration.

This indicator can be used as a metric of whether the generated runoff is greater than the generated evapotranspiration and infiltration (i.e. NHP>1).

Extended Life of Water (ELW):

$$ELW = \frac{WI_T}{AWI_T - ERW_T} \tag{C.25}$$

Where, AWI_T represents the volume of actual water input; and EWR_T is the volume of water output that is externally recycled.

The difference between WI_T and AWI_T is that the former accounts for all the water that would enter the system if no circularity actions were taken, while the latter accounts only for the actual water inflows of the system.

C.3.2.2 Energy Indicators

Renewable Energy Contribution (REC):

$$REC = \frac{REU}{E_T} \quad \text{(C.26)}$$

Where, REU is the renewable energy in kWh that is used in the system to meet its energy demands; and E_T is the total energy demand of the system.

Energy Self-Sufficiency (ESS):

$$ESS = \frac{EP_{os}}{E_T} \quad \text{(C.27)}$$

Where, EP_{os} represents the energy in kWh that is produced on site and is used to meet its energy demands.

In this study, the REC and ESS indicators have the same value, since the energy obtained from the mains is non-renewable energy and the energy that is produced from the CHP unit is considered as renewable.

Energy Demand Minimization (EDM):

$$EDM = \frac{ED_0 - ED_1}{ED_0} \quad \text{(C.28)}$$

Where, ED_0 represents the energy demand of a baseline scenario; and ED_1 represents the energy demand of the investigated system.

In this study, for the baseline scenario is considered the energy that is consumed in the existing WWTP and for the energy demand of the HYDRO system, only the energy demand of HYDRO1 is considered, excluding the energy demand of the AGF.

Energy Production Efficiency (EPE):

$$EPE = 1 - \frac{LE}{EP_{os} + LE} \quad \text{(C.29)}$$

Where, LE represent the energy that is lost from the energy production system.

C.3.2.3 Resource Indicators

Circular Carbon Inflow (CCI):

$$CCI = 1 - \frac{CI_{NR}}{CR_T} \quad \text{(C.30)}$$

Where, CI_{NR} represents the non-renewable carbon input to the system; and CR_T represents the total carbon requirements for the system's operation.

In this study, the indirect non-renewable carbon input resulted from the use of electrical energy obtained from the mains is excluded.

Circular Carbon Outflow (CCO):

$$CCO = 1 - \frac{CO_W + CO_E}{CO_T} \quad \text{(C.31)}$$

Where, CO_w represents the amount of carbon that exits the system as a waste; CO_E represents the amount of carbon output that exits the system as direct emissions; and CO_T represents the total carbon output of the system, including CO_W, CO_E, the amount of carbon that is internally and externally recycled, and the amount of carbon that is consumed/stored within the system.

Circular Carbon Flow (CCF):

$$CCF = \frac{2 - (\frac{CI_{NR}}{CR_T} + \frac{CO_W + CO_E}{CO_T})}{2} \quad \text{(C.32)}$$

Extended Life of Carbon (ELC):

$$ELC = \frac{CM_T}{ACI - ERC} \tag{C.33}$$

Where, CM_T is the total amount of carbon that is managed in the system; ACI is the actual carbon input to the system; and ERC is the amount of carbon that is externally recycled.

Circular Nitrogen Inflow (CNI):

$$CNI = 1 - \frac{NI_{NR}}{NR_T} \tag{C.34}$$

Where, NI_{NR} represents the amount of nitrogen that enters the system from non-renewable sources; and NR_T represents the total nitrogen requirements of the system.

Circular Nitrogen Outflow (CNO):

$$CNO = 1 - \frac{NO_W + NO_E}{NO_T} \tag{C.35}$$

Where, NO_W represents the amount of nitrogen that exits the system as a waste; NO_E represents the amount of nitrogen output that exits the system as direct emissions; and NO_T represents the total nitrogen output of the system, including NO_W, NO_E, the amount of nitrogen that is internally and externally recycled, and the amount of nitrogen that is consumed/stored within the system.

Circular Nitrogen Flow (CNF):

$$CNF = \frac{2 - (\frac{NI_{NR}}{NR_T} + \frac{NO_W + NO_E}{NO_T})}{2} \tag{C.36}$$

Extended Life of Nitrogen (ELN):

$$ELN = \frac{NM_T}{ANI - ERN} \tag{C.37}$$

Where, NM_T is the total amount of nitrogen that is managed in the system; ANI is the actual nitrogen input to the system; and ERN is the amount of nitrogen that is externally recycled.

Circular Phosphorus Inflow (CPI):

$$CPI = 1 - \frac{PI_{NR}}{PR_T} \tag{C.38}$$

Where, PI_{NR} represents the amount of phosphorus that enters the system from non-renewable sources; and PR_T represents the total phosphorus requirements of the system.

Circular Phosphorus Outflow (CPO):

$$CPO = 1 - \frac{PO_W + PO_E}{PO_T} \tag{C.39}$$

Where, PO_W represents the amount of phosphorus that exits the system as a waste; PO_E represents the amount of phosphorus output that exits the system as direct emissions; and PO_T represents the total phosphorus output of the system, including PO_W, PO_E, the amount of phosphorus that is internally and externally recycled, and the amount of phosphorus that is consumed/stored within the system.

Circular Phosphorus Flow (CPF):

$$CPF = \frac{2 - (\frac{PI_{NR}}{PR_T} + \frac{PO_W + PO_E}{PO_T})}{2} \tag{C.40}$$

Extended Life of Phosphorus (ELP):

$$ELP = \frac{PM_T}{API - ERP} \tag{C.41}$$

Where, PM_T is the total amount of phosphorus that is managed in the system; API is the actual phosphorus input to the system; and ERP is the amount of phosphorus that is externally recycled.

Circular Organic Materials Flow (COMF):

$$COMF = \frac{2 - \left(\frac{OM_V}{OM_T} + \frac{OM_W}{OM_W + OM_R + OM_T}\right)}{2} \tag{C.42}$$

Where, OM_V is the amount of virgin organic materials that enter the system; OM_T is the total amount of organic materials that are used in the system; OM_W is the amount of organic materials that exit the system as a waste; OM_R is the amount of organic materials that are reused or recycled; and OM_T is the amount of the organic materials that are transformed within the system.

Circular Chemicals Flow (CChF):

$$CChF = 1 - \frac{Ch_N}{Ch_T} \tag{C.43}$$

Where, Ch_N is the amount of new chemicals that are used in the system; and Ch_T is the total amount of chemicals that are used in the system, including the amount of chemicals that are regenerated and reused within the system.

C.3.2.4 Waste and Emissions Indicators

Waste Eco-Efficiency Index (WEI):

$$WEI = \frac{W_T}{P_T} \tag{C.44}$$

Where, P_T is the total amount of products that are produced in the system; W_T is the total amount of waste that is generated in the system.

This indicator is translated as X kg of waste are generated per 1 kg of products.

Emissions Eco-Efficiency Index (EEI):

$$EEI = \frac{Em_T}{P_T} \tag{C.45}$$

Where, Em_T is the total amount of direct emissions that are generated in the system.

Similarly to the WEI, this indicator is translated as X kg of emissions are generated per 1 kg of products.

Waste Utilization Index (WUI):

$$WUI = \frac{W_U}{W_U + W_T} \tag{C.46}$$

Where, W_U is the amount of waste that is utilized to produce system's products.

Emissions Utilization Index (EUI):

$$EUI = \frac{Em_U}{Em_U + Em_T} \tag{C.47}$$

Where, Em_U is the amount of direct emissions that are utilized in the system.

Carbon Footprint (CF) and other LCA-based indicators:

$$CF_O = Em_F\ x\ EF + E_T\ x\ EF + Ch_N\ x\ EF \tag{C.48}$$

Where, CF_O represents the carbon footprint of the system's operation; Em_F represents the fugitive emissions of the system; and EF represents the different emission factors of the fugitive emissions, energy consumption, and chemicals that are used in the system in order to translate them into kg of CO_2 equivalents.

Embodied CF can also be incorporated to estimate the total CF of the system. Additional LCA-based indicators can be incorporated in the analysis as well.

C.3.2.5 Economic Indicators

Intrinsic Circularity Savings (ICS):

$$ICS = RR_1 \ x \ Price \ of \ RR_1 + \cdots + \ RR_Z \ x \ Price \ of \ RR_Z \qquad (C.49)$$

Where RR_1 represents the amount of resource that is internally recycled, contributing to system's monetary savings.

Intrinsic Circularity Revenues (ICR):

$$ICR = P_1 \ x \ Price \ of \ P_1 + \cdots + \ P_Z \ x \ Price \ of \ P_Z \qquad (C.50)$$

Where, $P_{1\text{-}Z}$ represent the amount of the different products that are produced and sold in the system, by considering only the additional products that are produced from circularity actions.

Total Revenues (TR):

$$TR = ICR + CR \qquad (C.51)$$

Where, CR represents the conventional revenues that are received whether or not circularity actions are taken.

Lost Revenues (LR):

$$LR = NVP_1 \, x \, Price \; of \; P_1 + \cdots + NVP_Z \, x \, Price \; of \; P_Z \tag{C.52}$$

Where, $NVP_{1\text{-}Z}$ represent the amount of the different not-valorised products (i.e. products that are not sold) that are produced in the system.

Payback Period (PP):

$$PP = \frac{CAPEX}{TR - OPEX} \tag{C.53}$$

Where, CAPEX is the total expenditure costs; and OPEX is the total operational costs per year.

In this study, the PP is estimated for circularity actions with and without energy reuse onsite and for the HYDRO1 without circularity actions.

C.3.2.6 Biodiversity Indicator

Simpson's Index of Diversity (D):

$$D = 1 - \left(\frac{\sum n(n-1)}{N(N-1)}\right) \tag{C.54}$$

Where, n is the total number of organisms (in this case plants) of a particular species; and N is the total number of organisms of all species.

This indicator takes values between 0 and 1. With this index, 1 represents infinite diversity and 0, no diversity.

C.3.2.7 Technical Indicators

Produced Food per functional unit (PF_{fu}):

$$PF_{fu} = \frac{Produced \; food \; [kg]}{Total \; volume \; of \; influent \; wastewater \; [m^3]} \tag{C.55}$$

Produced Compost per functional unit (PC_{fu}):

$$PC_{fu} = \frac{Produced\ compost\ [kg]}{Total\ volume\ of\ influent\ wastewater\ [m^3]} \tag{C.56}$$

Produced Energy per functional unit (PE_{fu}):

$$PE_{fu} = \frac{Produced\ energy\ [kWh]}{Total\ volume\ of\ influent\ wastewater\ [m^3]} \tag{C.57}$$

Produced Irrigation Water per functional unit (PIW_{fu}):

$$PIW_{fu} = \frac{Produced\ irrigation\ water\ [m^3]}{Total\ volume\ of\ influent\ wastewater\ [m^3]} \tag{C.58}$$

Discharged Water per functional unit (DW_{fu}):

$$DW_{fu} = \frac{Discharged\ water\ [m^3]}{Total\ volume\ of\ influent\ wastewater\ [m^3]} \tag{C.59}$$

Water Withdrawal Reduction per functional unit (WWR_{fu}):

$$WWR_{fu} = \frac{WW_0 - WW_1\ [m^3]}{Total\ volume\ of\ influent\ wastewater\ [m^3]} \tag{C.60}$$

Chemicals Intensity per functional unit (ChI_{fu}):

$$ChI_{fu} = \frac{Total\ amount\ of\ chamicals\ that\ are\ used\ in\ the\ system\ [kg]}{Total\ volume\ of\ influent\ wastewater\ [m^3]} \tag{C.61}$$

Carbon Footprint per functional unit (CF_{fu}):

$$CF_{fu} = \frac{CF_O \; [kg \; of \; CO_2 \; equivalents]}{Total \; volume \; of \; influent \; wastewater \; [m^3]} \quad \text{(C.62)}$$

Intrinsic Circularity Revenues per functional unit (ICR_{fu}):

$$ICR_{fu} = \frac{ICR \; [€]}{Total \; volume \; of \; influent \; wastewater \; [m^3]} \quad \text{(C.63)}$$

C.3.2.8 Ecosystem Services Indicators

The results of the ES indicators after the consultation of responsible partners are presented in Table C.8.

Table C.8: Qualitative assessment results for the ES in the agroforestry

Ecosystem Services - Qualitative Assessment				
ES category	**Indicator**	**Expected value**	**Description**	**Aggregated value**
Provisioning ES	Fresh water	o	There is no production of fresh water onsite	++
	Food	+	10 t of produced food per year	
	Fibre & Fuel	o	Neutral impact since the site is not intended for fibre and fuel production. However, there is a potential for harvesting	
	Genetic resources	+	This is related to biodiversity. Although genetic/soil species biodiversity is not monitored yet, it is expected to have a positive contribution to this ES due to the increased variety of plants in the AGF system, the conservation tillage practices, and the incorporation of organic matter (both from green waste which will not be collected and from the application of compost).	
	Biochemicals / Natural medicines / Pharmaceuticals	+	7 plant species out of the 43 species can be used as natural medicines	
	Ornamental resources	+	It is expected that local people will enjoy flowers and other ornamental plants on the accessible agroforestry. However, further investigation is required through questionnaires to the visitors of the AGF.	
Regulatory ES	Air quality regulation	+	Increase of vegetation diversity, including tall herbs and tree plantings could make a substantial difference to air quality, especially considering the neighbouring WWTP. Increased vegetation contributes to particulate fallout, adsorption of metals and metabolism of nitrous oxides, ozone and other pollutant gases (see for example Nowak et al., 1998 and 2002).	++

	Climate regulation (local temperature, GHG sequestration, etc.)	+	Local temperature in the AGF site is expected to be decreased. Carbon sequestration in AGF (soil organic content and standing crop) is expected to be slow during the early part of tree growth, but will pick up as the trees mature until it levels off after its full maturity. Long-established tree stands have only limited potential for sequestering additional soil C (Takimoto et al., 2008a Takimoto et al., 2008b)	
	Water regulation	+	Based on the results of NHP indicator	
	Natural hazard regulation (storm protection)	N.A.	Uncertainty about this service	
	Pest regulation	N.A.	Uncertainty about this service	
	Disease regulation	N.A.	Uncertainty about this service	
	Erosion regulation	+	AGF systems are found to have an increased potential in erosion control (Torralba et al., 2016).	
	Water purification	o	There is no water body downstream the AGF system, so this service is expected to be negligible.	
	Pollination	+	Restoration of habitat and AGF systems can restore stocks of natural pollinators which may be beneficial for the local population by increasing their interest in cultivation.	
Supporting ES	Soil formation	+	Soil formation will be enhanced by improved and diversified habitat, as well as by the annual application of soil conditioner. Soil formation further contributes to carbon sequestration and erosion regulation.	++
	Primary production	+	Primary production will be enhanced by improved and diversified habitat. This service is further depicted in food and fibre & fuels services.	
	Nutrient cycling	+	Enhanced habitat will contribute to nutrient spiralling and transformation (for example via vegetative uptake, nitrification, denitrification and related ecosystem processes).	
	Water recycling	+	This service is depicted in water regulation and it is based on the NHP indicator results.	
	Photosynthesis (production of atmospheric oxygen)	+	Photosynthetic oxygen generation will be enhanced by improved and diversified habitat, especially due to the incorporation of tall trees onsite. This service contributes to primary production and air quality regulation services as well.	
	Provision of habitat	N.A.	Uncertainty about this service. It is expected to provide habitat to birds but further observations are required.	
Cultural ES	Cultural heritage	N.A.	Uncertainty about this service	+
	Recreation & tourism	+	Local visitors, tourists and schools are expected to visit the site. The minimum walking distance to the site is approximately 17 minutes.	
	Aesthetic value	+	The design and plants selection of the AGF system was performed in a co-creation activity with the local	

		community in order to increase the aesthetic value of the site.
Spiritual & religious value	N.A.	Uncertainty about this service
Education resources / Knowledge systems	+	Schools will use agroforestry for educational purposes. Five school visits per year are expected.
Social relationships	+	The restoration provides opportunities for the creation of local interest. However, further investigation is required through questionnaires to the visitors of the AGF

C.4 Sensitivity Analysis Results

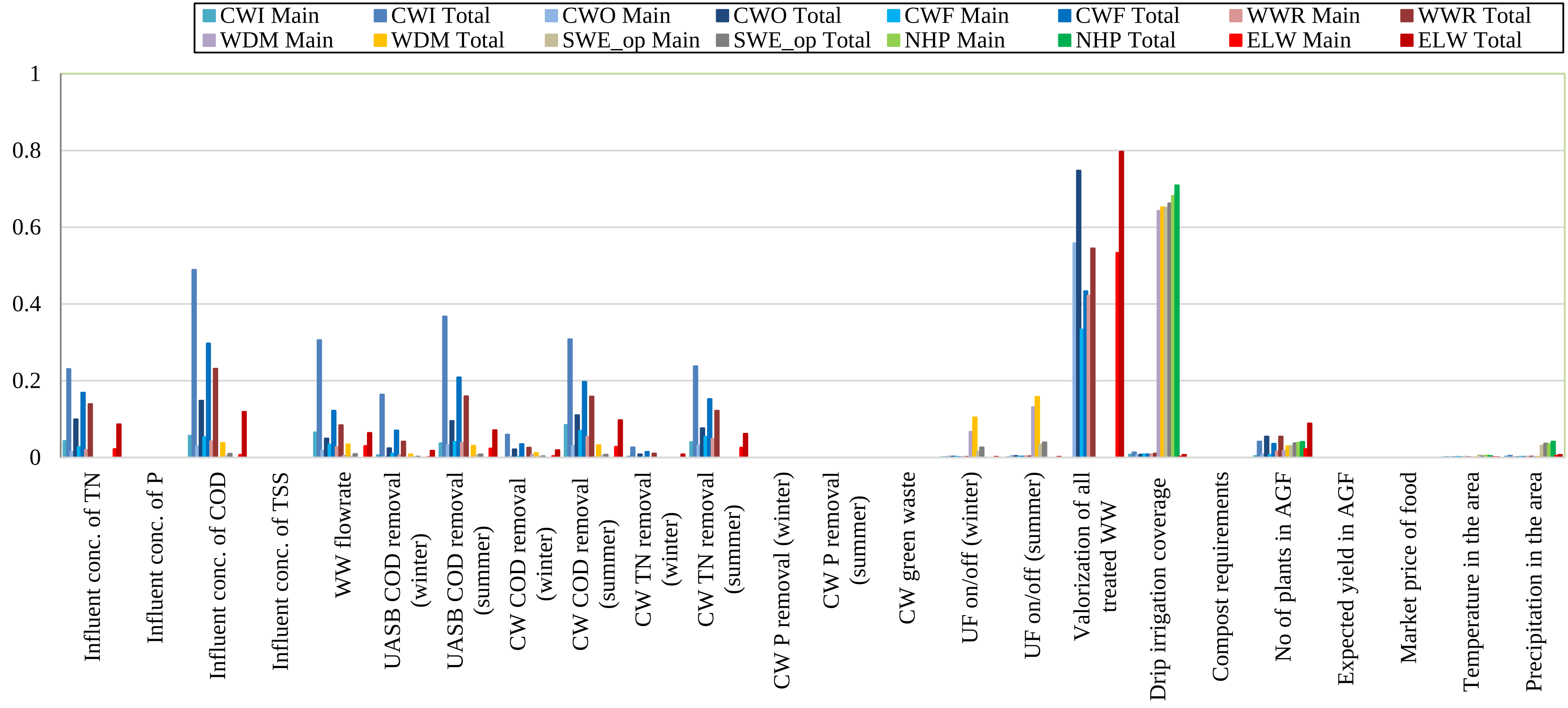

Figure C.2: Sensitivity Analysis results for the water-related indicators

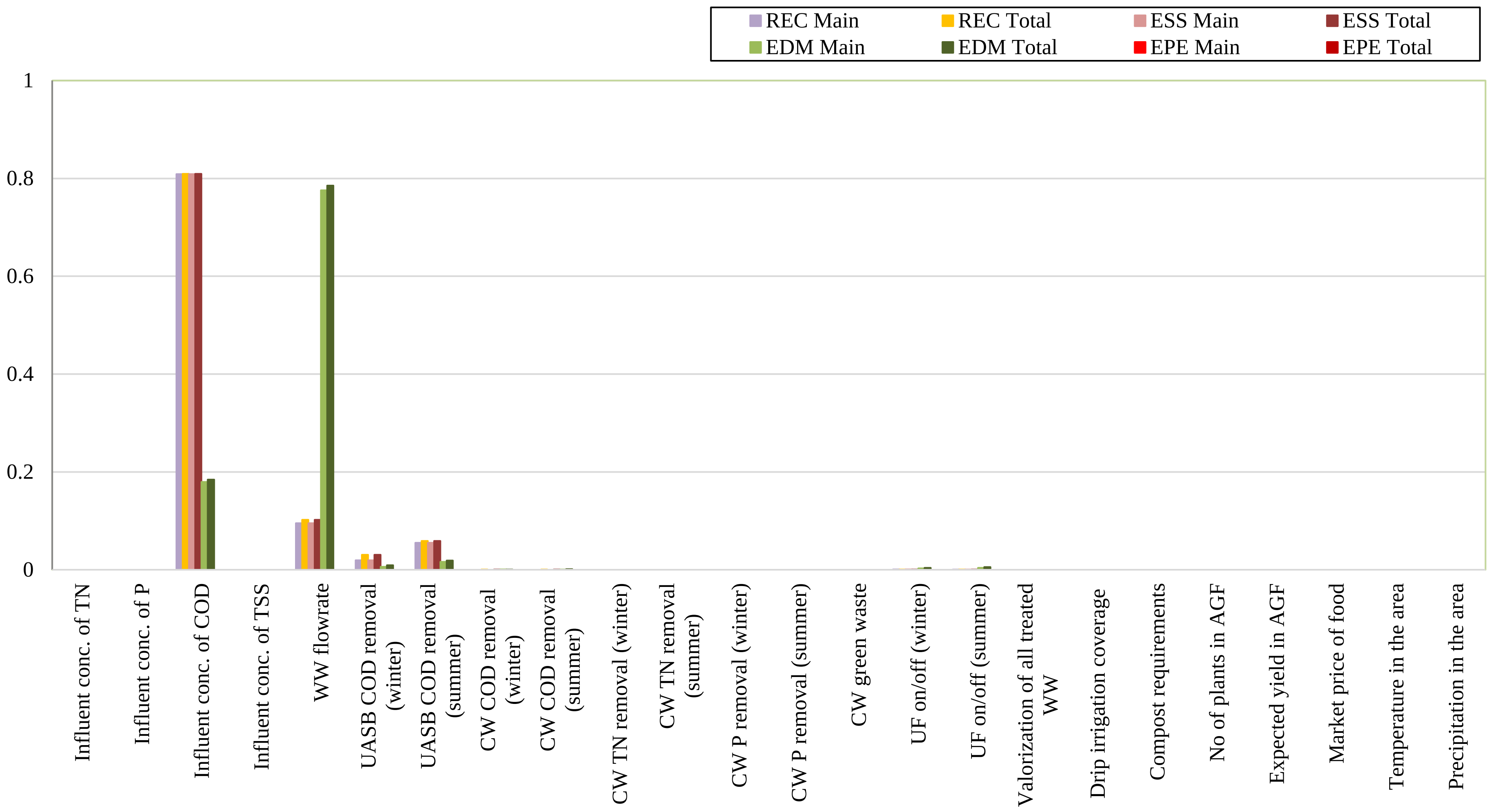

Figure C.3: Sensitivity Analysis results for the energy-related indicators

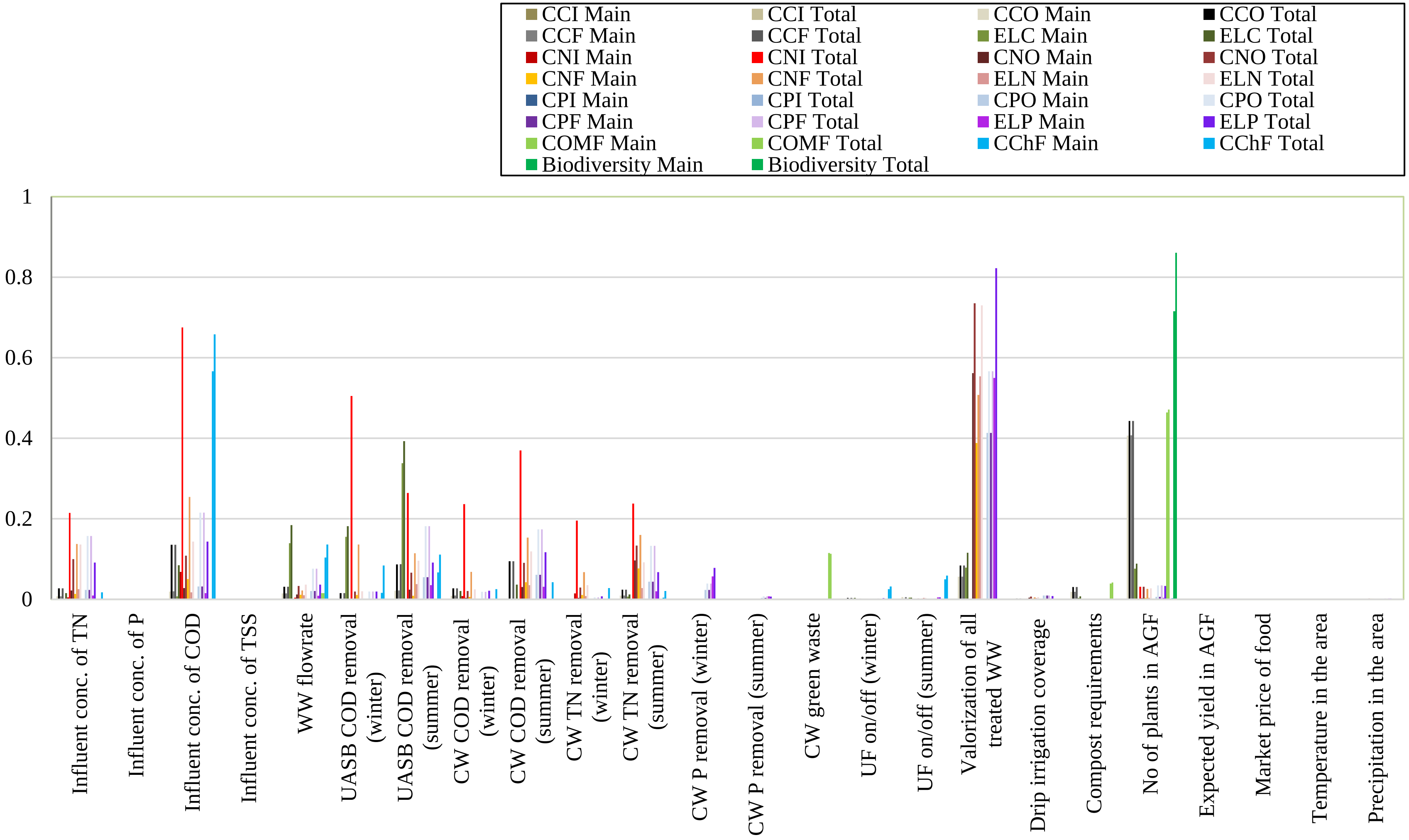

Figure C.4: Sensitivity Analysis results for the resource-related & biodiversity indicators

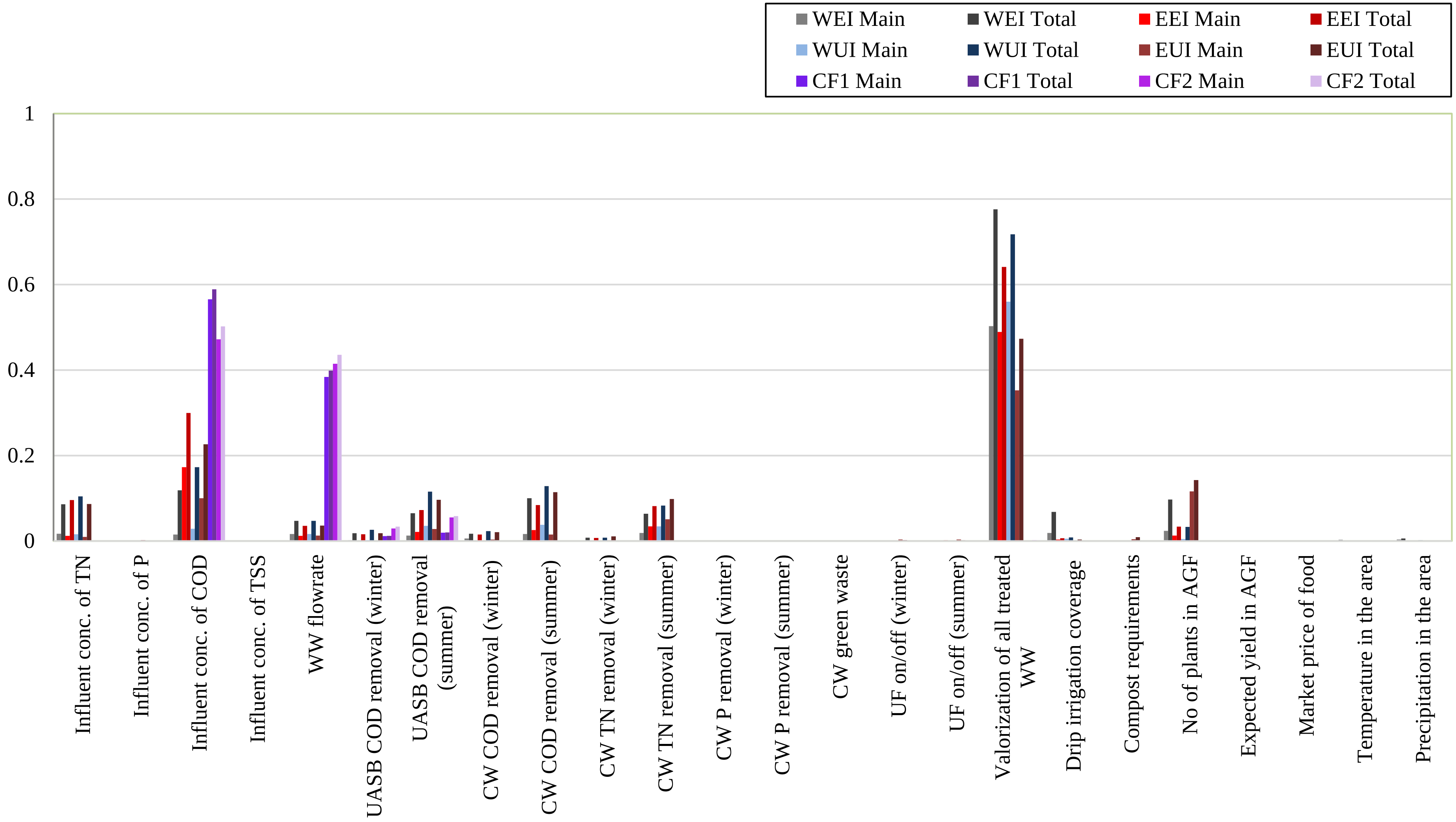

Figure C.5: Sensitivity Analysis results for the waste & emissions indicators

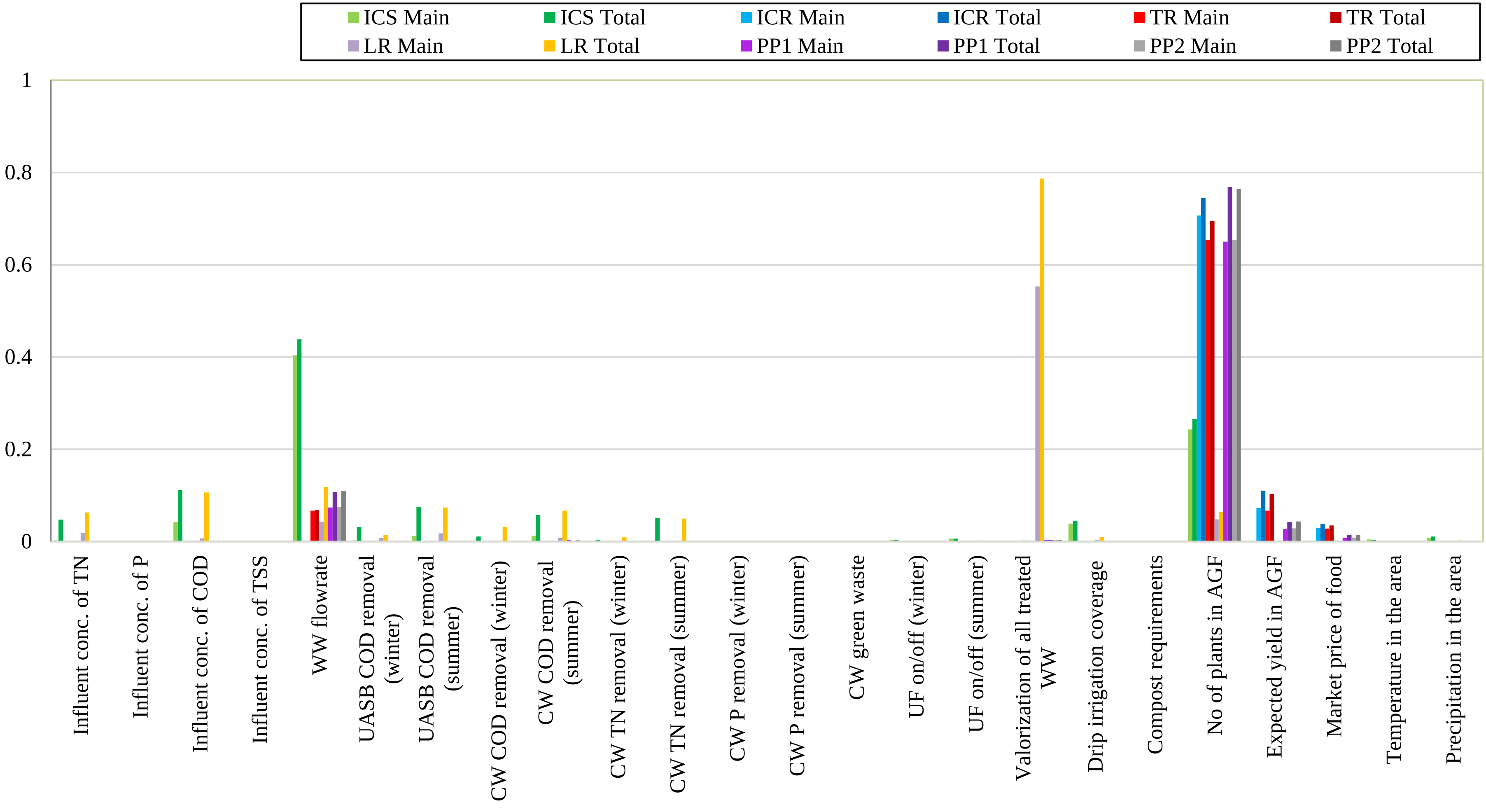

Figure C.6: Sensitivity Analysis results for the economic indicators

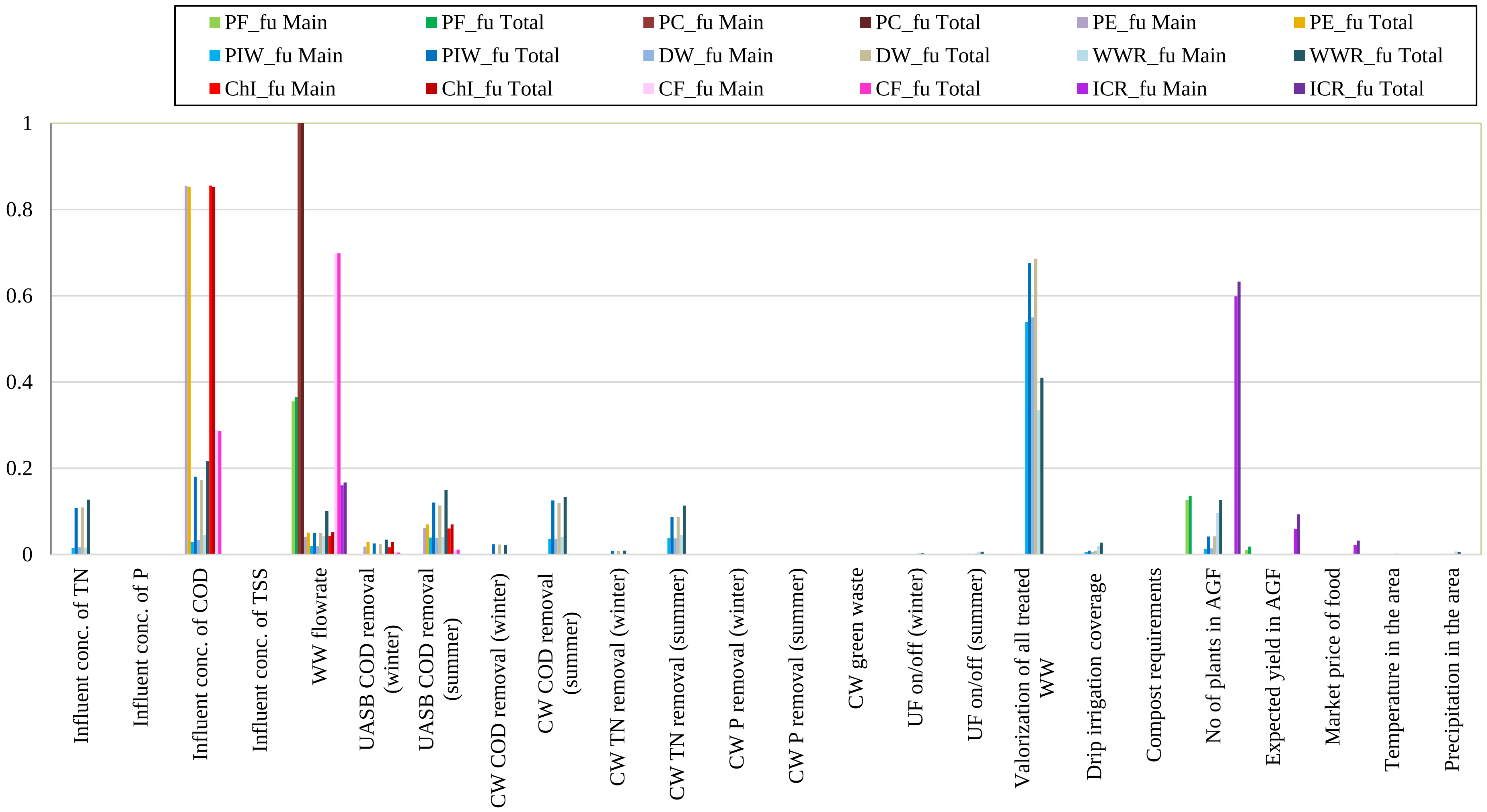

Figure C.7: Sensitivity Analysis results for the technical indicators

C.5 References

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