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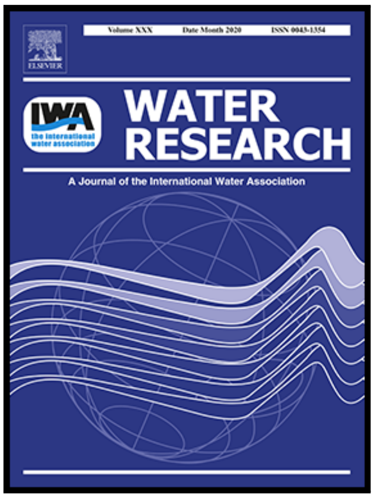

Assessing circularity of multi-sectoral systems under the Water-Energy-Food-Ecosystems (WEFE) nexus

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Highlights

- Expanded-MSWCA for systematic Circular Economy indicators selection
- 67 circularity indicators related to 13 Sustainable Development Goals
- The retrofit system outcompetes the baseline in terms of circularity performance
- Circularity performance optimization of retrofit system by 8-61%
- The optimized system mitigates lurking circularity risks of uncontrollable events

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

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Abstract

The Multi-Sectoral Water Circularity Assessment (MSWCA) is a methodological framework developed for circularity assessment of the Water-Energy-Food-Ecosystems nexus. It involves five methodological steps and includes an indicators list for the selection of case-specific indicators. This study expands the MSWCA to provide a systematic approach for selecting indicators, considering system's circular actions and multi-functionality, the capture of implemented changes, the three CE principles and the Sustainable Development Goals. Furthermore, this study differentiates between benchmark and dynamic circularity assessment and applies the expanded MSWCA in a water system of the HYDROUSA H2020 project. The benchmark assessment indicates that the HYDROUSA system achieves a 75% increase of water circularity, 76-80% increase of nutrients circularity and 14% reduction of operational `carbon footprint compared to the baseline scenario. The dynamic assessment highlights that additional measures can improve the system's circularity performance (e.g. water circularity can reach 94%) and mitigate risks occurring from uncontrollable changes.

Keywords: Multi-Sectoral Water Circularity Assessment; Nature-based Solutions; Circular Economy Indicators; Water-Energy-Food-Ecosystems nexus; Sustainable Development Goals

1. Introduction

As the concept of Circular Economy (CE) is gaining momentum, research has been increasingly focused on circularity measurement and assessment. 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), considering system, sector, and/or 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).

Even though there are extensive numbers of CE indicators in literature (see e.g. Helander et al., 2019; Moraga et al., 2019), existing indicators fail to measure the CE holistically and systemically (Corona et al., 2019; Haupt and Hellweg, 2019; Walzberg et al., 2021), which may further lead to the undesirable self-selection of indicators by organizations resulting in biased or narrow assessments (Pauliuk, 2018). For the adoption of more holistic approaches, more complex composite indicators are being developed to capture additional aspects within CE assessments. For example, the Wastewater Circonomics Index (Kayal et al., 2019) evaluates circular performance of technologies by measuring production, recycling and reuse efficiencies under monetary terms, while the Water Utility Performance Composite Indicator (D'Inverno et al., 2021) weights and aggregates 8 indicators across economic, financial, environmental (with percentage water loss the only environmental indicator) and service prevision factors for monitoring utilities' performance under the CE transition. Although composite indicators are useful for simplifying complex information, they may provide a narrow view of the overall circularity and/or sustainability performance. This brings into perspective the advantage gain by using composite indicators, as no indicator exists which encompasses all aspects of the CE concept, compared with robust selection of indicator sets. It has been shown that single-focus indicators are required to identify trade-offs, whilst users of composite indicators need to compromise between the comprehensiveness and complexity of analysis (Jerome et al., 2022). Therefore, multiple indicators must be considered for holistic assessments, meaning that systematic and robust methods for indicator selection are paramount.

In the water sector, which is mandated to be approached from a nexus perspective according to the new CE Action Plan (EC, 2020), only a few studies have focused on the identification and selection of CE indicator sets. A database of 270 indicators for sustainability assessments of CE initiatives is selected and then refined to ensure relevance of indicators and that all triple bottom line (TBL) dimensions are considered (Kravchenko et al., 2020). A dynamic indicator selection process based on stakeholder participation and application of the Interpretive Structural Model (ISM) is also suggested (Nika et al., 2021), providing information regarding the interrelationships, and prioritization of indicators for analyzing complex systems. However, this approach is reliant on expert opinion and participation across multiple rounds of questioning. To overcome the vagueness and ambiguity of expert judgements, the fuzzy-Delphi methodology is applied to select social CE indicators (Padilla-Rivera et al., 2021), combining qualitative surveying of CE experts with quantitative analysis to decide on key indicators. A final ranking for the indicators analyzed is provided, where the user is able to decide the threshold of acceptability. For the agri-food sector, 102 indicators are classified and summarized in a dashboard, according to the TBL, spatial levels (macro, meso, micro) and 8 scopes related to the function of the indicator (such as water, waste, and knowledge and innovation) (Poponi et al., 2022). The results highlight a lack of indicators related to economic and social aspects of air, water, soil, energy and waste scopes for all spatial levels, requiring further development.

Following selection, indicators should be implemented based on a thorough assessment methodology, so results provide all the relevant information for robust decision making, especially as circular systems provide additional complexities compared with linear processes (Furness et al., 2021). Therefore, structured methodologies are required for rigorous assessment of circular systems, such as the Multi-Sectoral Water Circularity Assessment (MSWCA) framework (Nika et al., 2020a). The MSWCA framework assesses circularity of complex systems under the Water-Energy-Food-Ecosystems (WEFE) nexus and proposes a thorough list of indicators that can 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. Although the MSWCA indicators database can be used as a reference for case-specific indicators selection, the existing form of the framework does not include specific considerations and detailed steps for the selection. Other methodological studies focus on the sustainability performance of WWTPs by combining life cycle assessment (LCA) and life cycle costing (LCC) (Shanmugam et al., 2022) or on the economic feasibility of circular systems by developing a framework for Shadow-Pricing Life Cycle Cost-Benefit that highlights the importance of considering economic impacts of environmental and social benefits (Ghafourian et al., 2022). However, both studies focus more on the consequential rather than the intrinsic circularity (Saidani et al., 2019).

The current study aims to develop consensus on circularity measurement and assessment of water systems under the WEFE nexus. Based on the MSWCA, this study develops specific methodological steps (Section 2) that enable a systematic approach for the indicators' selection process (i.e. circularity measurement) and validates the methodology by applying it to a case study developed within the HYDROUSA H2020 project (Section 3). This study further differentiates for the first-time benchmark from dynamic circularity assessment. The results of this differentiation (Section 4) show that dynamic assessment provides valuable insights on the impact of operational changes to system's circularity performance and can be used to prevent and mitigate lurking risks to circularity and sustainability.

2. Methodological Approach developed for Circularity Measurement and Assessment

The current work builds on the MSWCA framework and develops a methodological approach for circularity measurement and assessment, focusing on indicators selection and on two different types of assessment. Figure 1(a) illustrates the existing form of the MSWCA framework, Figure 1(b) indicates in green the methodological modifications developed in this study, and Figure 1(c) represents in detail the indicator selection step.

[Figure 1]

As shown in Figure 1(a), the ***System development step*** in the initial form of the MSWCA includes the identification of unit processes and targeted resource flows of the system in focus. In this study, this step is expanded to include the identification of circular action(s) implemented in the system, potentially creating a new multi-functional system (Figure 1(b)). Circular actions indicate the activities or solutions implemented to enable the realization of CE and its principles. The identification of circular actions specifies what needs to be measured and assessed, enabling the selection of appropriate circularity indicators. The next step introduced in this study deals specifically with the circularity ***Indicators selection*** (Figure 1(b)). As the circularity indicators should have a significance and a meaning to the system in focus (i.e. to be able to measure system changes occurred by the circular actions), the selection of suitable circularity indicators is case-specific (Kambanou and Sakao, 2020). As illustrated in Figure 1(c), there are three indicator taxonomy branches applied for both construction and operation phase of the system; i.e. indicators for circular actions (or performance indicators for system's multi-functionality), indicators for resource flow circularity measurement (differentiated into resource inflow/outflow, water, energy, waste and emissions indicators), and indicators for sustainability impacts (differentiated into economic, environmental and social impacts and values indicators). The indicators are then categorized according to the 3 CE principles (EMF, 2018) and their relation to the Sustainable Development Goals is identified, ensuring the selection of a holistic set of circularity indicators. For this purpose, the LinkedSDG (United Nations, 2020) online tool can be used that automatically identifies keywords related to sustainable development from documents and connects them to the most relevant SDGs and targets. The next methodological step (Figure 1(b)) is the ***Circularity measurement*** that includes primary and secondary data collection, as well as the development of a system model to produce tertiary data required for the calculation of the selected indicators. In case that the selected indicators cannot be calculated by primary, secondary or tertiary data, the indicators selection step is repeated to identify alternative indicators. In the ***System testing*** step, sensitivity analysis is performed to investigate the effectiveness of the selected indicators to capture changes in the system – occurred from the implementation of circular actions – and thus, to identify the main operational variables that affect system's performance. In case the selected indicators are not able to capture system's changes, new indicators need to be selected. The ***Circularity assessment*** step is now differentiated between benchmark and dynamic circularity assessment. Benchmark assessment uses static data and/or models to evaluate the system and compare it with the baseline scenario, while dynamic assessment focuses on the optimization of the system by using scenario analysis, continuous monitoring data and/or dynamic modelling. The final step of ***Prediction of circularity performance*** is included in Figure 1(b) but not applied in this study.

The developed methodological approach is applied to the HYDROUSA case study in the next section to test its applicability and enhance its understanding.

3. Methodology

3.1. System Development – 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 in an existing WWTP, treating the domestic wastewater of Antissa village (population of 5,269 at the 2011 census), and of a new agroforestry system (HYDRO2) – considered as an NBS – located at the surroundings of HYDRO1. Figure 2(a) shows the HYDRO system implemented onsite and Figure 2(b) illustrates the treatment train and production of the HYDRO system. More specifically, HYDRO1 receives domestic wastewater from the pre-treatment unit and treats it by combining 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. 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. The yielded crops and fruits are sold in the local market. The Sankey diagram of Figure 2(c) illustrates the (waste)water (in blue) and water-related (i.e. COD in green, nitrogen in red and phosphorus in purple) resources as they flow through and are transformed within the different processes of the system. Additional resources required for system's operation – presented in Figure

2(b) – include chemicals in the CHP and UF units, water for the CHP and compost units and energy for all system's processes. The generated products (Figure 2(b)) include fertigation water, compost, energy and food, while the produced solid and liquid waste (including losses), as well as the gaseous and water emissions are considered as system outputs as well.

[Figure 2]

The following circular actions implemented in the HYDRO system are identified:

- Upgrading of treated wastewater to fertigation water, adding value to treated water as well as to the carried nutrients, and consequently reducing the need for freshwater resources and fertilizers for agriculture by recycling them to HYDRO2;
- Repurposing of generated sludge into valuable compost, adding value to the carried nutrients and to the sludge itself – which otherwise would be treated as waste – and consequently reducing the need for further chemical fertilizers use in HYDRO2, as well as the generated waste and its impacts;
- Repurposing of generated biogas (i.e. mixture of CO_2 and CH_4) to produce energy that can be reused onsite, adding value to the produced methane that otherwise would be emitted, and consequently reducing the need for fossil energy and the generation of GHG emissions;
- Land recycling for the development of an agroforestry system, regenerating the value of the abandoned land that surrounds the WWTP and further producing a diversity of food and crops while creating ecosystem services, such as increased biodiversity, improved soil structure and health, reduced erosion, and carbon sequestration;
- Implementing CW as an NBS that contributes to the circular design of the system by using natural processes to treat wastewater, resulting in green land recycling and showcasing that a filtration unit – mandated by the Greek regulations – is no longer needed, reducing the chemicals and energy needs of the system; and

- Fostering the reduction of water use in agriculture by using drip irrigation system versus supporting cultural heritage of the local community's practice of using a stone channel irrigation system.

The identified circular actions contribute to all three CE principles and result in the creation of a potential multi-functional system compared to the previous mono-functional system that aimed 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. Therefore, the goal of the assessment is to evaluate the circularity performance and the sustainability impacts (benefits and costs) of the WWTP before and after the implementation of the HYDRO system (i.e. benchmark assessment), as well as to investigate the optimization of the HYDRO system in terms of circularity criteria under different operational scenarios, focusing on the interaction between HYDRO1 and HYDRO2 (i.e. dynamic assessment).

The system boundary shown in Figure 3 has been selected for the assessment. Figure 3 presents the foreground processes for which data was collected to be fed in the developed model that measures circularity, and background processes that are available in the Ecoinvent® database. The construction phase (including production of materials and energy, transportation of materials and construction work onsite) of the HYDRO system is included in the boundary, while the construction phase of the existing WWTP is excluded due to lack of available data. The operation phase includes all incorporated resources of both the HYDRO system and the existing WWTP to measure the generated waste and emissions, the economic impacts, circularity of resources, and additional environmental benefits (i.e. ecosystem services). Upstream stages of the water supply chain, downstream market, users and end-of-life impacts are out of the scope of this study.

[Figure 3]

3.2. Indicators Selection for the HYDRO system

Following the systematic indicators selection approach developed and presented in Section 2, a list of circularity indicators is selected (Table 1), considering the system boundary, resource flows and circular actions.

[Table 1]

Seventeen performance indicators (Table 1) are selected considering the circular actions and system's multi-functionality (see Section 3.1). For the circular action of land recycling, the land use, green and grey land recycling indicators (EEA, 2018) are used, while the impacts of this action are measured with the soil sealing and land densification indicators (EEA, 2018) presented in the environmental & social impacts and values category of Table 1. The agroforestry system produces food, contributing to the systems multi-functionality – measured with the PF_{fu} indicator – and resulting to additional environmental and social impacts and values, which are measured with the natural hydrological performance indicator (modified from Renouf et al., 2017), the Simpson's index of diversity, as well as the provisioning, regulatory, supporting and cultural ecosystem services indicators. For the circular action of treated wastewater upgrade, the produced irrigation water (PIW_{fu}) is measured that results in a change of the discharged wastewater (DW_{fu}). This contributes to numerous resource flow circularity indicators (i.e. CCI, CCO, CCF, ELC, CNI, CNO, CNF, ELN, CPI, CPO, CPF, ELP, CWI, CWO, CWF, ELW) – obtained and modified from WBCSD, 2021 and Enel S.p.A., 2018 – further impacting the water withdrawal reduction indicators (WWR_{fu} and WWR). The sludge repurposing action is measured with the performance indicator of produced compost (PC_{fu}), while the resource flow circularity is measured with the corresponding C, N, P indicators, as well as with the COMF indicator. Nutrients recirculation through fertigation water and compost application to the agroforestry further impacts the use of mineral fertilizers, measured with the chemicals use intensity indicator (ChI_{fu}). For the biogas repurposing action, the performance indicators of energy production (PE_{fu}) and energy production efficiency (EPE) are selected, which would impact energy and C circularity indicators (i.e. CCI, CCO, CCF, ELC, ESS, REC), while the use and regeneration of the required chemicals for the CHP operation is measured with the CChF indicator. The ESS indicator is obtained and modified from Leusbrock et al. (2015). The implementation of the CW and their impact to the operation of the

UF unit is measured with the performance indicators of ChI_{fu} and the energy demand minimization (modified from Agudelo-Vera et al., 2012). This indicator is expected to be impacted by the selected irrigation systems as well, the performance of which is further measured with the system's water efficiency (SWE) and the water demand minimization (WDM) indicators. Complementary indicators to capture additional impacts and values of the system are included in Table 1. These indicators are related to waste and emissions performance and circularity indicators (i.e. WEI, WUI, EEI and EUI – modified from Villarroel Walker et al., 2009), economic impacts and values (i.e. ICR, TR, LR, ICS and PP) and the carbon footprint (CF) of the system. To complete the indicators selection, resource flow circularity indicators for the construction phase are included in Table 1. This phase is measured using indicators differentiating between the type (i.e. renewable and non-renewable) and source (i.e. virgin, recycled and reused/repurposed) of built materials, water and energy use, as well as generation and utilization of waste. The economic and environmental impacts of the construction phase are measured with the capital expenditure (CAPEX) and the carbon footprint, respectively. All equations used to calculate the selected indicators of Table 1 – as well as their units – can be found in Section 2 (Eq. 1 – 57) of the Supplementary Material.

Using the definitions of the 3 CE principles (Nika et al., 2020a) the selected indicators were further categorised according to the principle they represent. Table 1 shows that all 3 CE principles are targeted by the selected indicators. More specifically, 29 indicators target the Keep resources in use principle, 16 indicators target the Design out negative externalities principle, and 14 indicators target the Regeneration of natural capital/environment principle. The economic indicators are not categorised as their representation is based on the aspects that can be monetized.

Finally, the selected indicators of Table 1 are used in the LinkedSDG tool to identify their relation to the 17 SDGs and their incorporated targets. The input document to the online tool can be found in Supplementary Material and the results are presented in Figure 4.

[Figure 4]

Figure 4 indicates 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 sustainability aspects.

3.3. Circularity measurement of the HYDRO system

The circularity measurement step is applied to the HYDRO system for the calculation of the construction and operation phase indicators. For the construction phase indicators, collected primary data (Table SM.1) combined with the background processes (Figure 3) are used for the calculation. The calculations can be found in Table SM.3, while the final results are presented in Table 3. For the HYDRO's system operation phase, collected primary and secondary data (Table SM.2), as well as background processes are used in a developed model to calculate the operation phase circularity indicators. The developed model consists of an anthropogenic sub-system (i.e. HYDRO1), a nature-managed sub-system (i.e. HYDRO2) and their node of intersection. A detailed description of the model can be found in Section 3 of the Supplementary Material.

All the selected indicators of Table 1 (apart from the ES indicators) can be quantified by the model. A modelling procedure to estimate all the ES indicators would overcomplicate and increase the uncertainty of the developed model. Therefore, these indicators are 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).

3.4. System Testing – Sensitivity Analysis of selected indicators

The variance-based global sensitivity analysis is selected to gain insight into the robustness of the indicator 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 Table SM.2. The results of the sensitivity analysis in terms of main and total sensitivity indices for all the calculated indicators can be found in Figures SM. 1 – 6.

Figure 5 illustrates the results of the sensitivity analysis in terms of median value, 5^{th} and 95^{th} percentiles of the indicators. It should be noted that among the 48 selected indicators, 3 indicators are static; i.e. changes in the input variables do not influence these indicators. These are related to energy efficiency (i.e. EPE) and to circularity of carbon and phosphorus input (i.e. CCI and CPI). The remaining 45 indicators can capture system's changes thus, there is no need to repeat step 2 of the methodological approach. The selected set of indicators is used for the assessment.

[Figure 5]

In Figure 5(a), the 5^{th}, 95^{th} percentiles and median values of 13 indicators (i.e. SWE, REC, ESS, EDM, CCO, CCF, ELC, CNI, CNF, COMF, CChF, EUI, PC_{fu}) present small variation; these indicators are expected to change only when significant changes or certain operational conditions occur in the system. This indicates that there is a reduced probability of investigated operational conditions significantly affecting the results of these indicators. The remaining 32 indicators of Figure 5 are more prone to variations, suggesting that these indicators are the most unstable and more operational conditions would impact them, further affecting the circularity performance of the system.

Table 2 presents the most sensitive indicators for each tested variable, considering the main and total indices. 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 scenarios selection (Section 3.5). By comparing the indicators of the main and total indices in Table 2, it is evident that 8 variables (highlighted in blue) influence different indicators, showing that the developed model is able to capture the occurrence of interdependencies between different system's components.

[Table 2]

The results of Table 2 indicate that 14 out of the 48 selected indicators (i.e. CWI, ELC, CNO, EUI, ELP, ChI_{fu} EDM, CCF, CNI, COMF, WDM, NHP, biodiversity and ICR) are the most sensitive to changes in input variables according to the main indices, while according to the total indices, 12 out of the 48 indicators (i.e. CWI, ELC, CPO, ELP, REC, EDM, CNI, COMF, WDM, NHP, biodiversity and ICR) are the most sensitive to changes that occur synergistically by the input variables. Amongst them the CWI, CPO, ELP, WDM, NHP, ICR are more prone to change (Figure 5) and more sensitive to input variables (Table 2). Thus, these indicators are the most likely to play a key role in the overall circularity performance of the system and are sensitive to operational and system control decisions. These indicators can be integrated in decision making to evaluate the circularity performance of the system under dynamic conditions and in practice link operational decisions with circularity performance.

3.5. Circularity Assessment – Benchmark & Dynamic assessment

Benchmark circularity assessment:

The comparison of the WWTP before and after its upgrade to the HYDRO system is based on a reduced set of circularity indicators. From the selected performance indicators (Table 1), the indicators related to land recycling and irrigation system are excluded as they cannot be measured for the existing WWTP. The EPE indicator is excluded as a static indicator, while the WEI and EEI are not used as they provide additional information to the WUI and EUI indicators, respectively. From the resource flow circularity indicators, the circular resource inflow and outflow indicators are presented in their aggregated form (i.e. circular resource flow), while indicators related to other resources are excluded as additional indicators. From the economic impacts and values indicators, the ICR and TR indicators are used as the most representative of this category, while the NHP indicator of the last category provides an additional benefit of HYDRO system that can be represented by the ES indicators for the benchmark assessment. The construction phase indicators – calculated only for the HYDRO system – can be used as a reference for future comparison with other similar systems that are newly built. The indicators can be also used to identify the circularity hotspots during construction. The results of the benchmark circularity assessment are presented in Section 4.1.

Dynamic circularity assessment:

The dynamic circularity assessment requires scenario analysis that would enable circularity performance optimization of the HYDRO system. Using the sensitivity analysis results for the selection of the scenarios, the five identified influential variables (presented in bold in Table 2) 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 for circularity performance failure. This way, optimization of system's operation is suggested by increasing the overall circularity performance and reducing risk. Based on these considerations, the following scenarios are investigated:

- Scenario 0 (current, HYDRO system): current operational status of the HYDRO system; it can be found in Section 1 of the Supplementary Material
- 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 (i.e. sold to the local economy instead of being discharged); 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 mitigation of negative impacts occurred from the worst non-controllable scenario

The results of the dynamic assessment consider the operation phase indicators only and indicate under which scenario the system obtains a better circularity performance. These 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. These results are presented and discussed in Section 4.2.

4. Results and Discussion

4.1. Benchmark Assessment

The benchmark circularity assessment results – presented in Table 3 – include the construction and operation phase, as well as the expected result of each ES category expressed in qualitative terms.

[Table 3]

The construction phase results in Table 3 indicate that mainly virgin (99.74%) and non-renewable (100%) materials are used for building the HYDRO system, generating 50,000 kg of waste that ends up in landfill. The embodied carbon in the construction materials, contributes significantly (~74%) to the carbon footprint of the construction phase (i.e. 170,552 kg of CO_2 eq.). While system's construction has a positive impact of natural environment regeneration principle – due to green land recycling – it has not followed the principles of keep materials in use (i.e. ~0% of recycled/reused/repurposed built materials used) and design out negative externalities (i.e. embodied carbon of built materials and generated waste). The use of recycled/reused materials or the selection of materials with low embodied carbon should be considered in similar systems to improve the circularity performance of their construction.

The operation phase results in Table 3 indicate that the HYDRO system outcompetes the baseline scenario in terms of circularity performance, economic, social and environmental impacts. Looking at the water and resource flow indicators, the baseline scenario achieves a circular water/carbon/nitrogen/phosphorus flow (i.e. CWF, CCF, CNF and CPF) of 50% but extended life is not achieved for any of these resources (i.e. ELW/C/N/P = 1). The circular resource flow of 50% is achieved due to the fact that all resource inflows are characterised as recycled (i.e. circular flow), but all resource outflows are discharged to the sea thus, lost from the watershed (i.e. non-circular flow). The treated wastewater that is not returned to the watershed further impacts the value of the water withdrawal reduction (i.e. WWR = 0). If in the baseline scenario an agroforestry unit irrigated with freshwater is included, then the WWR indicator equals -0.22, indicating that additional water is lost from the watershed. The HYDRO system increases the values of the CWF, CCF, CNF and CPF indicators by 50%, 54%, 60% and 52%, respectively and further extends the life of these resources (ELW = 1.3, ELC = 1.63, ELN = 1.27 and ELP = 1.37). Due to the fact that treated wastewater is recycled to the agroforestry and some system processes (e.g. CHP and compost unit) use recycled water for their operation, water withdrawal is reduced by 59% in the HYDRO system. These resource flow circularity indicators quantify the effects of the treated wastewater upgrade, repurposing of sludge and biogas circular actions. The internal and external recycling of resources to generate products of the HYDRO system has further resulted in utilizing 34% and 54% of the otherwise disposed waste and produced emissions, respectively. The baseline scenario does not utilize any of its produced waste or emission (WUI, EUI = 0). Regarding the energy-related indicators, HYDRO1 consumes 1.69% more energy compared to the baseline (EDM = 0 as a reference point), but 23% of its energy needs are covered onsite by renewable energy sources (i.e. biogas). However, if the energy consumption of the CHP unit is excluded from the comparison HYDRO1 consumes 8.78% less energy compared to the baseline, indicating the contribution of NBS implementation as a circular action. In this case, it is assumed that the UF unit could be bypassed as the regulatory limits for the BOD_5 (10mg/L) and TSS (10mg/L) are met at the effluent of the CW (i.e. 6.30mg of TSS/L in winter and summer, and 4.47 and 6.82mg of BOD_5/L in winter and summer, respectively).

Regarding the performance indicators (Table 3), the baseline discharges 1m^3 of treated wastewater, produces 8.28kg of CO_2 eq. and gains 2.50€ for every m^3 of wastewater it treats. In comparison, for every m^3 of treated wastewater, the HYDRO system produces 0.57kg of food, 0.18kg of compost, 1.79kWh of energy, 0.39m^3 of irrigation water, 7.11 kg of CO_2 eq., discharges 0.58 m^3 of treated wastewater, 0.82 m^3 of freshwater are saved, and gains 6.16€. The difference between the TR_{fu} of the baseline and the HYDRO indicates the economic value added to the system due to the circular actions (i.e. 3.66€/ m^3 of treated wastewater or 56,857€/year). Additionally, it should be noted that the CF_{fu} value for the HYDRO system excludes the embodied CF of the construction phase, as well as the CF related to the energy consumption in agroforestry. Furthermore, 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 circular action of land recycling for the development of an agroforestry system, the experts consulted for the qualitative evaluation of the HYDRO expect that the system will have a positive contribution to all ES categories. The 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 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 ES and verify the experts' expectations on the contribution of NBS to the regeneration of natural systems.

4.2. Dynamic Assessment – Scenario Analysis

The results of the benchmark circularity assessment showed that the HYDRO system obtains a better circularity performance compared to the baseline. However, the benchmark circularity assessment is unable to show if the HYDRO system could further optimize its circularity performance by changing controllable operational conditions. Furthermore, there is a need to investigate whether changes to non-controllable operational conditions would pose a risk to circularity performance of the system and in case they do, to investigate the possibility of risks mitigation by changing the controllable variables. The results of this analysis (i.e. dynamic circularity assessment) are presented in Table 4.

[Table 4]

A comparison between the three controllable scenarios (i.e. Scenario 0, 1 and 2) shows that Scenario 0 achieves the lowest overall circularity performance (i.e. red shading indicator values), indicating that although the current operational conditions of the HYDRO result in a better circularity performance compared to the baseline, there is still room for circularity optimization of the system. The best circularity performance of the HYDRO system is achieved with Scenario 1, as indicated with green shading in Table 4. Under this scenario, the CWF of the system is 94% (increase of CWO indicator from 51% in Scenario 0 to 88% in Scenario 1); the life of water is extended to 2.44 and none of the treated wastewater is discharged to the sea ($DW_{fu} = 0$). The same trend is observed for the N and P indicators; i.e. CNF = 93%, ELN = 1.84, CPF = 95% and ELP = 2.75 compared to 80%, 1.27, 76% and 1.37 for the same indicators of Scenario 0, respectively. The C, energy, organic material and chemical related indicators are almost the same between the three controllable scenarios. Significant is the difference between the waste-related indicators for which, Scenario 1 achieves 88% of waste utilization – compared to the 34% achieved by Scenario 0 – resulting in 7.11kg of products for every kg of waste that is generated by the system. Marginal differences are observed for the emission-related indicators that result in a CF of 8.43kg of CO_2 eq. compared to the 8.52 kg of CO_2 eq. of Scenario 0, as well as for the economic indicators (except from the LR indicator). The value of CF_{fu} for Scenario 0 in Table 4 is higher compared to the value presented in Table 3 as in this case the embodied carbon of the construction phase and the agroforestry unit are included to the calculation.

Regarding the circular action of irrigation system selection, which could not be evaluated in the benchmark circularity assessment, the impacts are observed in the values of the WDM, SWE, NHP, EDM, $CF_{(fu)}$ and ICS indicators. The water-related indicators perform better in Scenario 1 compared to Scenario 2 due to the reduced water losses. Therefore, a water demand minimization of 20% and a system's water efficiency of 69% are achieved with drip irrigation. Furthermore, the additional irrigation water applied to the agroforestry by the open channels has a negative impact to the natural hydrological cycle of the system as indicated by the NHP indicator that increases from 0.42 in Scenario 1 to 0.68 in Scenario 2. Although the generated runoff in the agroforestry increases in Scenario 3, the NHP value is still less than 1 – indicating that infiltration and ET are still the dominant processes of the system. However, the variance of the NHP value indicates a potential risk of negative impacts on the natural hydrological cycle of semi-natural systems due to anthropogenic decisions and management. On the other hand, the reduced energy required for the operation of the open channels was expected to positively affect the total energy consumption and consequently the CF of the system. However, the EDM is the same between the two scenarios (i.e. open channels consume slightly less energy compared to drip irrigation), the CF_{fu} is reduced by 0.03kg of CO_2 eq./m^3 of treated wastewater and the ICS increases by 474€/year. Therefore, the use of drip irrigation only is suggested if there is no need to use open channels from a cultural heritage perspective.

Regarding the non-controllable scenarios (i.e. Scenario 3 and 4), the main positive changes occurred in the system are observed 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 by any other tested scenario. Although the influent COD concentration is a non-controllable variable, 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.

On the other hand, it is evident that if the conditions of Scenario 3 occur in the system, an increased risk to circularity failure would be posed for 32 out of the 48 indicators. Under the occurrence of Scenario 3, the values of these 32 indicators are significantly deteriorated to such an extent that the system no longer has a circular behaviour for many of these indicators (i.e. WWR= ~0; ELW= ELN = ELP = 1; WUI = 0; ICR is almost negligible; PP is significantly extended; PF_{fu} = PIW_{fu} = 0; and DW_{fu} = ~1).

The negative impacts of Scenario 3 can be mitigated to a large extent if operation of the system is optimized. This is studied in Scenario 5; the non-controllable conditions of Scenario 3 and the controllable operational conditions switched to Scenario 1 (optimum operation). The results show that under optimized operation, the system is able to significantly reduce the impacts related to water (i.e. from 4% to 100% for the CWO and WWR, from 42% to 90% for the CWF and from 1 to 2.8 for the ELW – compared to Scenario 3), resources (e.g. from 57% in Scenario 3 to 79% in Scenario 5 for the CNF and from 56% in Scenario 3 to 95% in Scenario 5 for the CPF), waste & emissions (e.g. for every kg of waste generated in Scenario 3, 0.3 g of products are produced; while in Scenario 5, every kg of waste corresponds to 2.5 t of products), and most of the performance indicators (with most significant being the ICR and PP).

Scenario 5 suggests that the current analysis can help identify mitigation measures to ensure the circularity performance of the system under sub-optimum influent compositions and size of the agroforestry unit. Negative impacts remain mainly for the biodiversity, PF_{fu} and economic indicators, indicating their indirect connection. 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. Conclusions

The current work develops a methodological expansion of the MSWCA framework the operationalisation of which is tested in a system under the WEFE nexus, developed within the HYDROUSA H2020 project. The modified methodology allows a systematic selection of circularity and sustainability indicators and differentiates between benchmark and dynamic circularity assessment of the system. The suggested methodology can be complementarily used with studies focusing on both the development of indicators dashboards and indicators ranking using participatory approaches. This study introduces for the first time the concept of circular actions for the selection of appropriate indicators, which further considers circularity of resource flows, as well as economic, environmental and social impacts and values, and their relation to the CE principles and the SDGs is included as well. The measurability of the selected indicators is tested by considering the availability of primary, secondary and tertiary data, while their capability of capturing system's changes affecting circularity performance is verified using sensitivity analysis. This versatile approach results in a set of case-specific circularity indicators that captures circularity and sustainability aspects, avoiding cherry-picking of indicators.

The application of the developed methodology to the HYDROUSA case study resulted in a set of 49 operational phase indicators that target 13 out of the 17 SDGs. All indicators are quantified except from the ES indicators that are qualitatively evaluated. From the selected indicators, only 3 could not capture changes occurring in the system, while 6 indicators (i.e. CWF, CPO, ELP, WDM, NHP and ICR) were identified as the most representative to assess circularity performance, since they are more prone to change and more sensitive to input variables. The 24 operational indicators as well as the ES indicators used in the benchmark circularity assessment indicate that the HYDRO system outcompetes the baseline in terms of circularity performance. The dynamic circularity assessment highlights that the HYDRO system does not operate under its optimum conditions and could significantly improve its circularity performance by using drip irrigation only and by further valorising the remaining treated wastewater (Scenario 1). If the system continues to operate under the current operational conditions and non-controllable changes are occurred, a risk for circularity performance failure is lurked. However, the negative impacts can be mitigated if the system is optimized under Scenario 1. Dynamic circularity assessment can therefore help identifying the real circularity potential as well as the hidden circularity risks of the system and can further suggest mitigation measures.

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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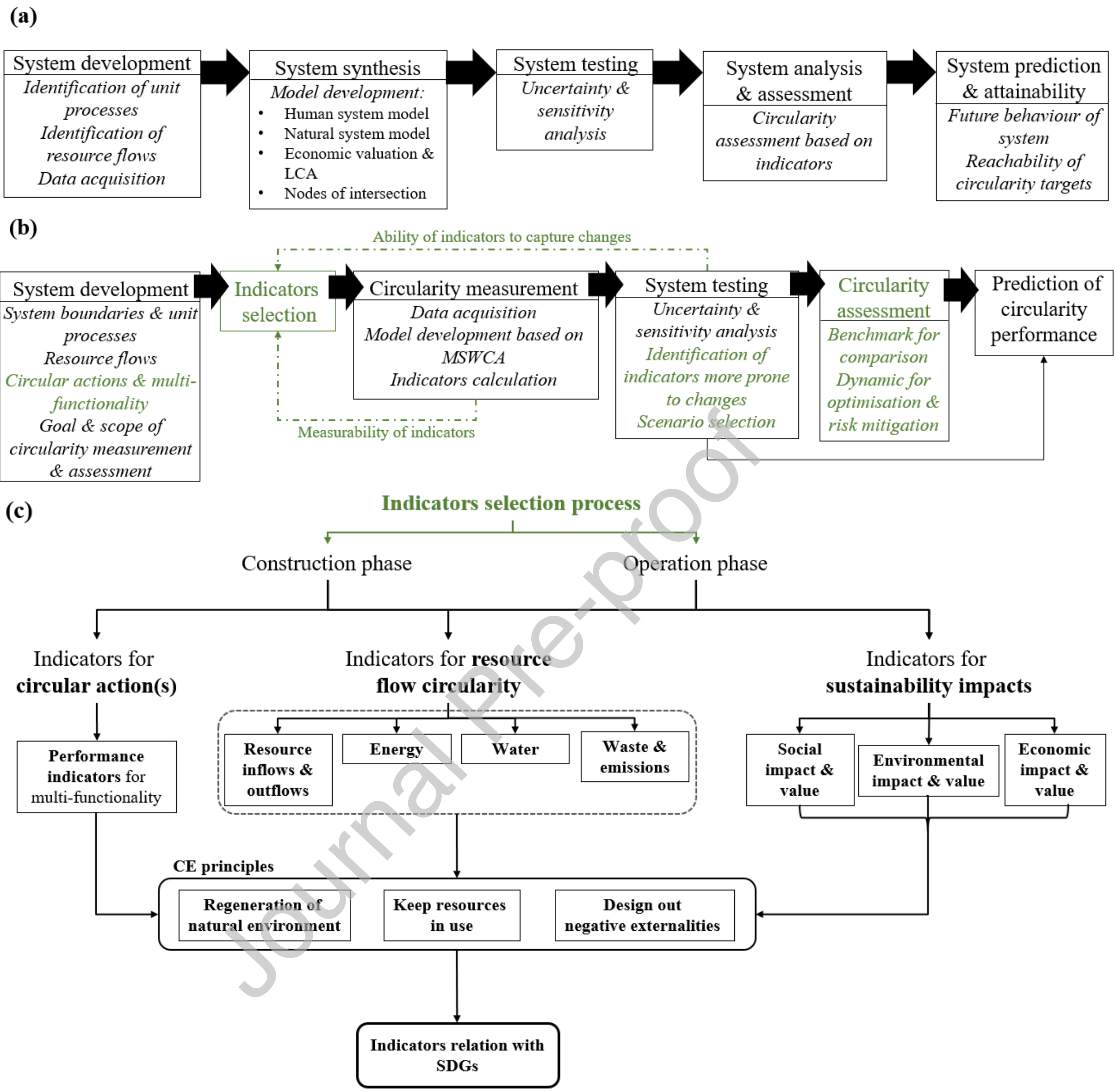


Figure 1. Previous form of the MSCWA (ex-MSWCA) **(a)**; New form of the MSWCA developed in this study (i.e. expanded-MSWCA) **(b)**; Indicators selection step of the expanded-MSWCA **(c)**

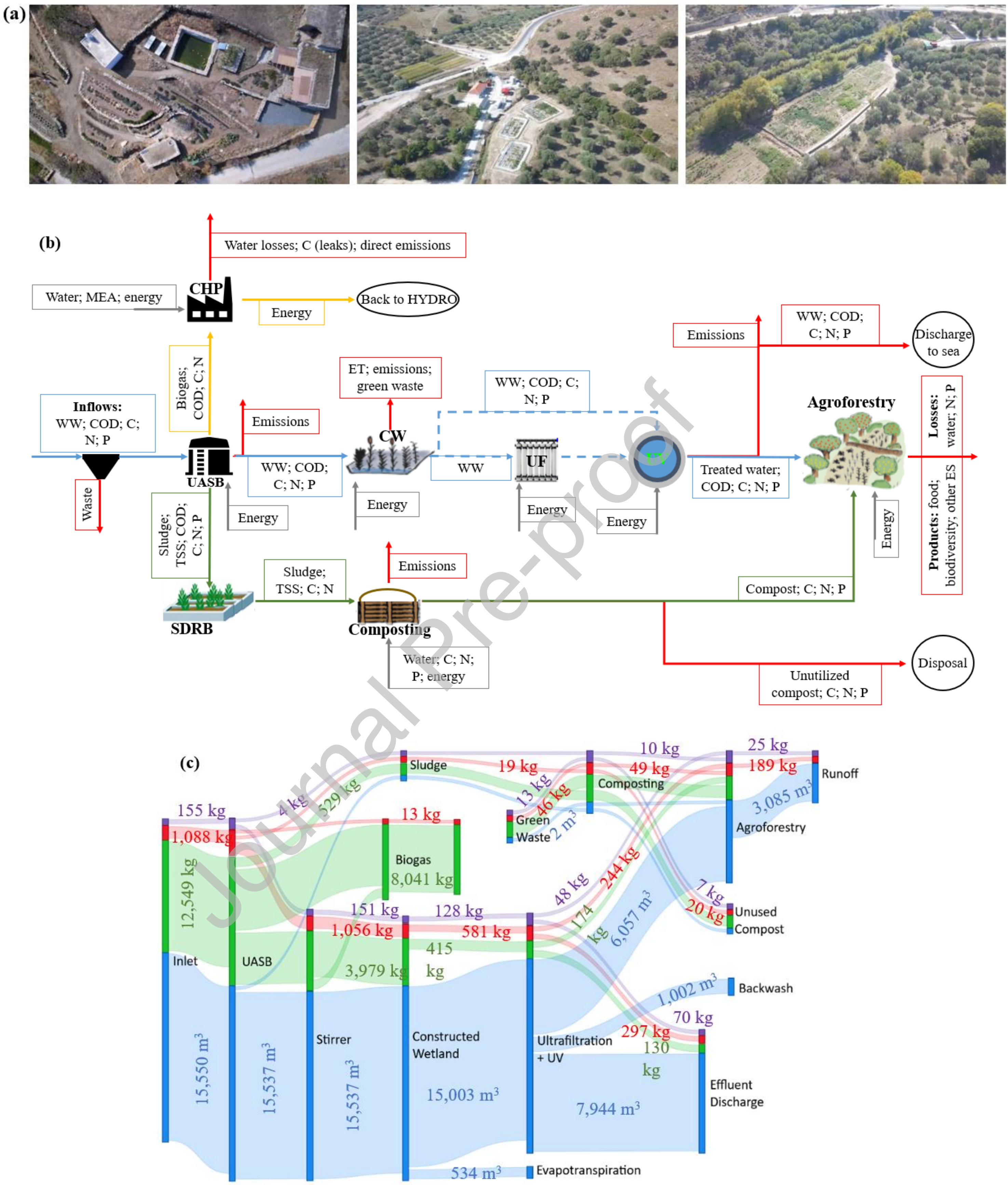


Figure 2. Aerial photos of the HYDRO system **(a)**; HYDRO system configuration **(b)**; Sankey diagram of the HYDRO system **(c)**

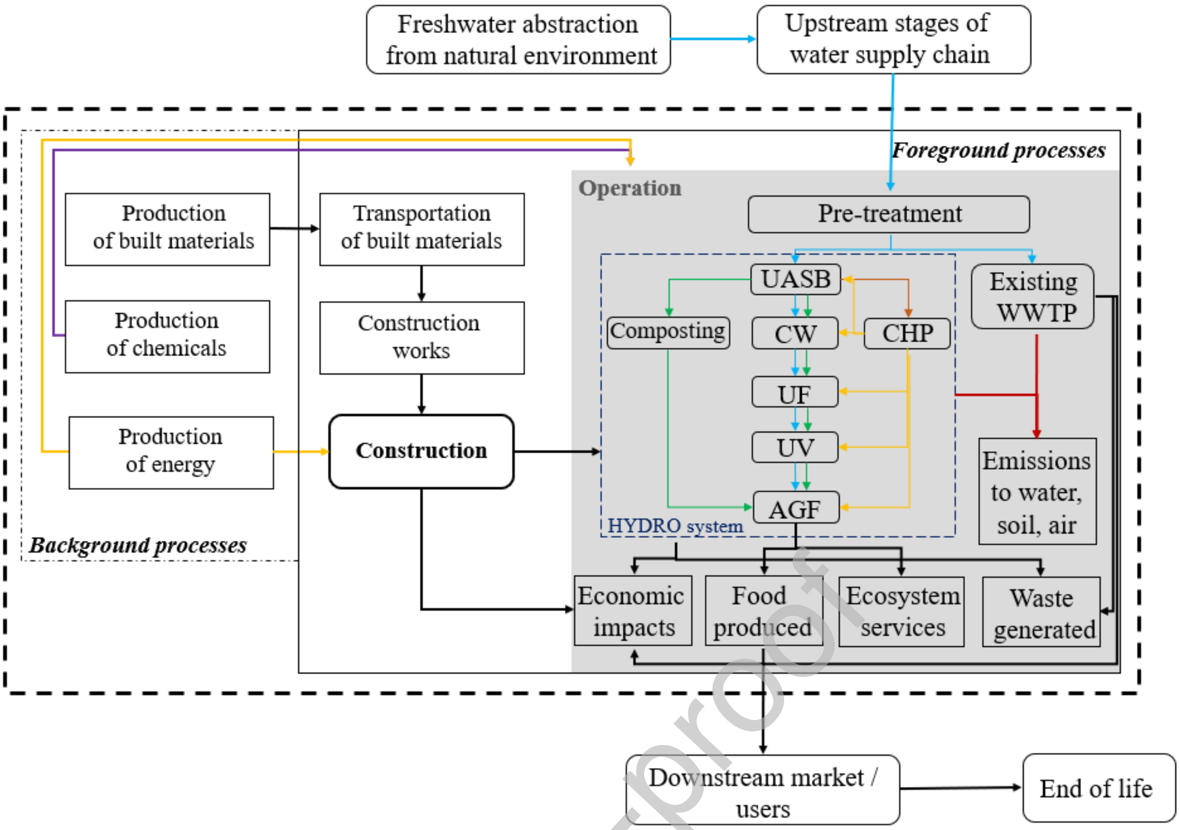


Figure 3. System boundaries of material, water/wastewater, energy, resources, waste, emissions, economic streams and ecosystem services for the study

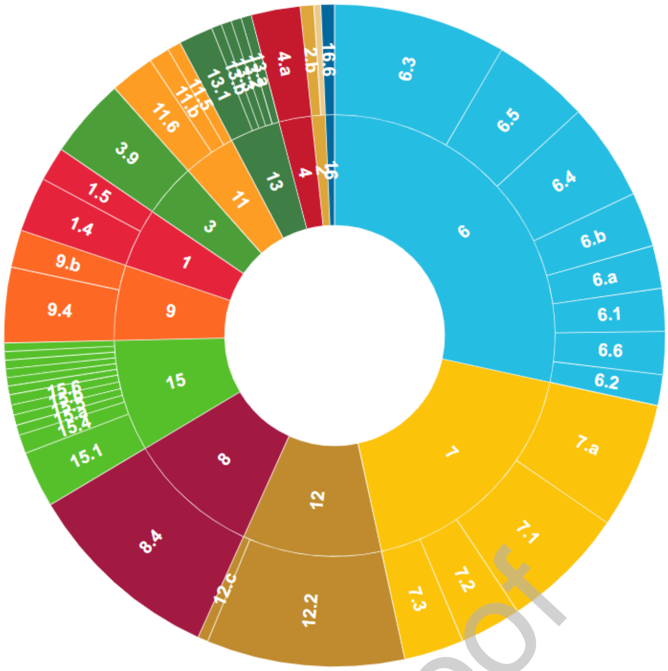
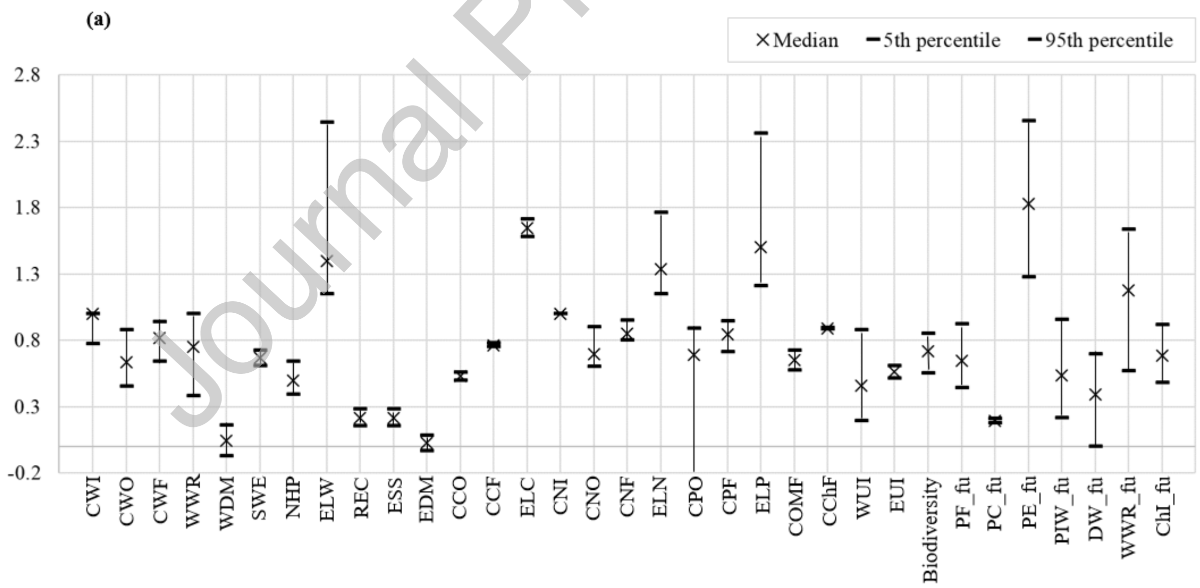


Figure 4. Representation of the relative weight of the SDGs and targets measured by the selected indicators



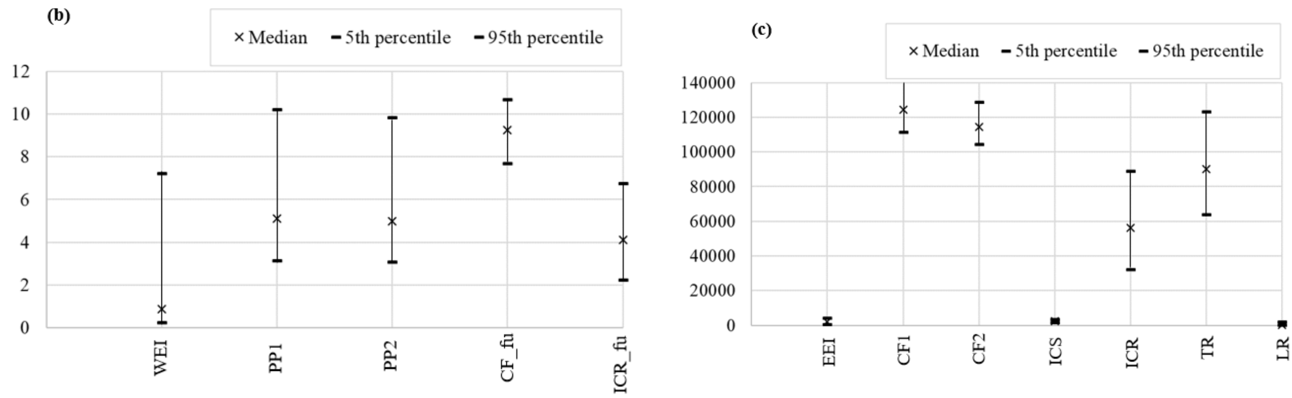


Figure 5. Results of the sensitivity analysis showing the median (x), 5[th] and 95[th] (-) percentiles of the distribution for all the investigated indicators

Table 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

	Construction Phase	***Circular Actions***						**Overall actions**
		Treated WW upgrade	*Sludge repurposing*	*Biogas repurposing*	*Land recycling**	*NBS for circular design*	*Irrigation system*	
Performance Indicators	See *Land recycling** indicators	Irrigation water per m^3 of treated WW (PIW_{fu})	Produced compost per m^3 of treated WW (PC_{fu})	Energy production per m^3 of treated WW (PE_{fu})	System's Land Use	Produced food per m^3 of treated WW (PF_{fu})	System's efficiency for operation (SWE)	Waste Eco-efficiency Index (WEI)
		Discharged WW per m^3 of treated WW (DW_{fu})		Energy production efficiency (EPE)	Green land recycling (GNLR)	Chemicals use intensity per m^3 of treated WW (ChI_{fu})	Water Demand Minimization (WDM)	Emission Eco-efficiency Index (EEI)
		Water Withdrawal Reduction per m^3 of treated WW (WWR_{fu})			Grey land recycling (GRLR)	Energy demand minimization (EDM)		Intrinsic Circularity Revenues per m^3 of treated WW (ICR_{fu})
Resourc Carbon (C) In / Out	-	Circular C Inflow (CCI) Circular C Outflow (CCO)		Circular C Flow (CCF)		Extended life of C (ELC)		

	Nitrogen (N)	In	-	Circular N Inflow (CNI)	Circular N Flow (CNF)	Extended life of N (ELN)
		Out		Circular N Outflow (CNO)		
	Phosphorus (P)	In	-	Circular P Inflow (CPI)	Circular P Flow (CPF)	Extended life of P (ELP)
		Out		Circular P Outflow (CPO)		
	Water	In	Water from the mains ($Water_{con.}$)	Circular Water Inflow (CWI)	Circular Water Flow (CWF)	Extended life of water (ELW)
			Alternative water source ($Water_{uncon.}$)			
		Out	-	Circular Water Outflow (CWO)		
	Energy		Non-renewable energy sources	Energy self-sufficiency (ESS)		
			Renewable energy sources	Renewable energy contribution (REC)		
	Other resources		Non-renewable materials intensity (NRNMI)	Circular Organic Materials Flow (COMF)		
			Renewable materials intensity (RNMI)	Circular Chemicals Flow (CChF)		
			New materials intensity (NMI)			
			Recycled materials intensity (RMI)			
			Reused / Repurposed materials (RUMI)			
	Waste & emissions		Remaining waste ($Waste_{rem.}$)	Waste Utilization Index (WUI)		
			Utilized waste ($Waste_{util.}$)	Emission Utilization Index (EUI)		
Economic			CAPEX	Intrinsic Circularity Revenues	Lost Revenues	Payback Period

impacts & values Indicators	Yearly CAPEX	(ICR) Total Revenues (TR)	(LR) Intrinsic Circularity Savings (ICS)	from circularity (PP)
Other environmental & social impacts & values Indicators	CF of built materials (CF_M), of transportation (CF_T), of construction works (CF_{CW}), avoided CF of reused materials (CF_{RM})	CF of operation	CF of operation per m^3 of treated WW	
	Soil sealing (SS)	Water Withdrawal Reduction (WWR)	Natural hydrological performance (NHP)	
	Land Densification (LD)	Simpson's Index of Diversity (plant species)	Provisioning ES Regulatory ES	Supporting ES Cultural ES

Table 2. 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

Table 3. 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 [%]	N.A.	100
	RNMI [%]	N.A.	0.00
	NMI [%]	N.A.	99.74
	RMI [%]	N.A.	0.00
	RUMI [%]	N.A.	0.26
Water	$Water_{con.}$ [%]	N.A.	100
	$Water_{uncon.}$ [%]	N.A.	0.00
Waste and Emissions	$Waste_{rem.}$ [%]	N.A.	100
	$Waste_{util.}$ [%]	N.A.	0.00
	CF_M [%]	N.A.	73.49
	CF_T [%]	N.A.	18.34
	CF_{CW} [%]	N.A.	8.16
	CF_{RM} [%]	N.A.	0.05
	CF_E [kg of CO_2 eq.]	N.A.	170,552
Economic	CAPEX [€]	N.A.	540,557
	$CAPEX_{annual}$ [€/year]	N.A.	31,485
Other	SS [%]	N.A.	2.69
	GNLR [%]	N.A.	97.3
	GRLR [%]	N.A.	2.69
	LD [%]	N.A.	10.64
	System's Land Use [m^2]	N.A.	10,631
Operation phase			
Water	CWF	0.50	0.75
	WWR	0.00; -0.22	0.59
	ELW	1.00	1.30
Energy	REC	0.00	0.23
	ESS	0.00	0.23
	EDM	0.00	-1.69; 8.78
Resources	CCF	0.50	0.77
	ELC	1.00	1.63
	CNF	0.50	0.80
	ELN	1.00	1.27
	CPF	0.50	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 [€/year]	0.00	56,857
Performance	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
	PIW_{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]	0.00; -0.31	0.82
	CF_{fu} [kg CO_2 eq./m^3 of treated WW]	8.28	7.11
	TR_{fu} [€/m^3 of WW treated]	2.50	6.16
Provisioning ES	Fresh water Food Fibre & Fuel	– –	++

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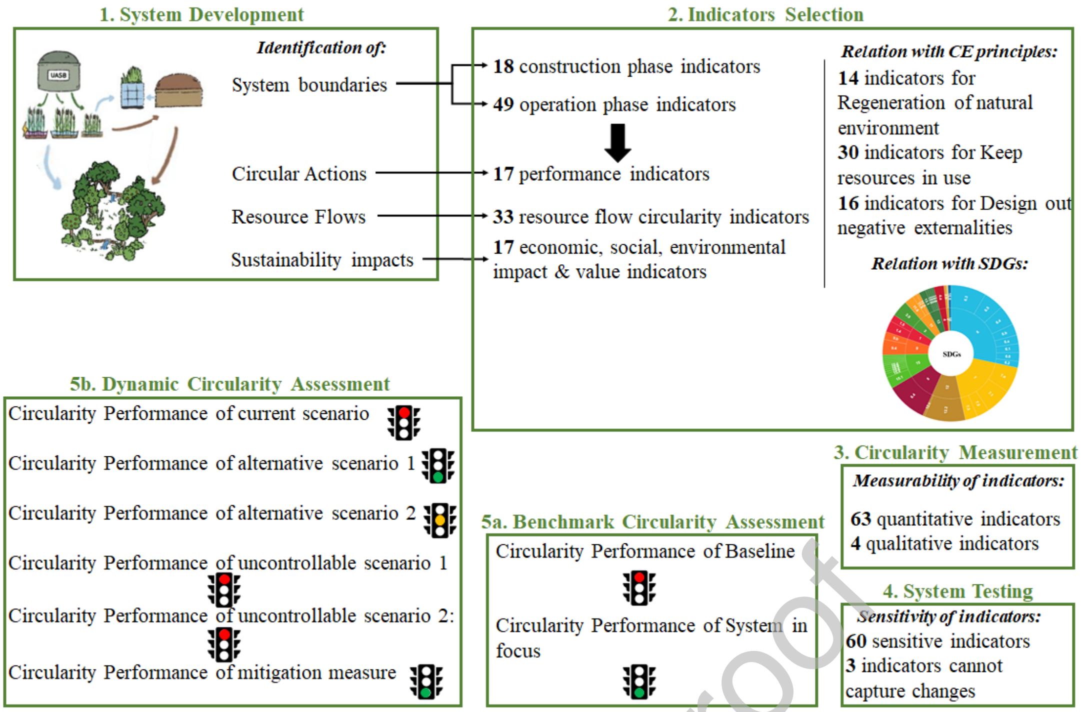
	Genetic resources Biochemicals Ornamental resources		
Regulatory ES	Air quality regulation Climate regulation Water regulation Natural hazard regulation Pest regulation Disease regulation Erosion regulation Water purification Pollination	– –	++
Supporting ES	Soil formation Primary production Nutrient cycling Water recycling Photosynthesis Provision of habitat	– –	++
Cultural ES	Cultural heritage Recreation & tourism Aesthetic value Spiritual & religious value Education resources Social relationships	– –	+

Table 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	2.83 ↑
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 ↑
Performance	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 ↑



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SDGs
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