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Unveiling green and nature-based solutions through innovative economic assessment- a case for circular water management system

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ABSTRACT

The impetus to move from aggressive environmentally damaging water management systems to sustainable alternatives is increasingly motivating both governments and investors. However, the economic justification for the often-heavy preliminary capital expenditure becomes a stumbling block. It is found that classical economic assessments fall short of monetising the environmental gains and being incorporated into economic assessments. To address this gap, the proposed method integrates the Pressure–State–Response (PSR) framework with cost–benefit analysis (CBA) and taking three steps of firstly identifying the necessity of implementing circular water system (CWS), second, conducting a holistic cost-benefit analysis considering internal and external impacts, and third providing decision-making support by reviewing and refining the outputs. For proof of concept, a case study for circular water and the relevant Nature based solutions (NBS) is presented that aimed to address Mykonos island's severe water shortages by developing new economic activities. Results show the feasibility of implementing the CWS in the investigated area, with a Payback period (PP) of 3.2 years, Net present value (NPV) of €30,906, Modified internal rate of return (MIRR) of 13%, and Benefit-cost ratio (BCR) of 6.2. The result calculated for the same system without considering environmental and social benefit illustrate a noteworthy difference in system viability. The sensitivity analysis of NPV revealed that the economic viability of the system improves as cash flow and reclaimed water tariffs, increase and the project's lifespan, Operational and maintenance cost (OPEX), and Capital cost (CAPEX) and discount rate decrease. In our view, green technologies should be economically assessed by measuring and monetising its environmental impacts, just as we do for conventional water management.

1. Introduction

1.1. Motivation

Nature-based solutions (NBS) are increasingly recognised for their potential to enhance urban resilience and sustainability [1,2]. NBS are defined as solutions that are inspired and supported by nature, offering multi-faceted benefits – environmental, social, and economic – in a cost-effective manner [3]. These solutions, grounded in the principles of working with nature, serve as a critical response to the challenges posed by urbanisation, which often disrupts the natural water cycle and imposes a linear “take-make-consume-dispose” model of water use. This linear model is not only environmentally unsustainable, leading to gradual degradation and deterioration of water quality as it moves through the system, but also poses significant economic challenges due to the unsustainable consumption and depletion of water resources [4,5]. To overcome these issues, a shift towards circular water management based on the Circular Economy (CE) principles emerges as a promising alternative to the inefficiencies and impacts caused by the linear pattern of water usage.

The transition to circular water systems requires enhancing existing grey water infrastructure through the integration of advanced intelligent technologies and substituting traditional industrial approaches with a mix of nature-based solutions and ecosystems, leading to the development of hybrid infrastructures that combine both grey and green elements [6–8]. Although the International Union for Conservation of

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Nature (IUCN) and the European Commission (EC) support the development of NBS in urban areas [3,9], their widespread adoption faces numerous obstacles [10]. Challenges such as stakeholder resistance and a general hesitance to finance NBS initiatives have been recognized as significant barriers (e.g., Kabisch et al., [11]; Van Jagt et al., [12]). Without a comprehensive and realistic economic assessment of modern intelligent technologies and NBS – accounting for their multifaceted benefits – the transition to circular water management risks remaining a theoretical concept [13]. Therefore, there is a need for a framework and mechanism that systematically incorporates social and environmental considerations into economic assessments and decision making.

The current study proposes a method for conducting a thorough economic analysis of green industrial systems with a specific attention to circular water systems by combining the Pressure, State, and Response (PSR) model, with an established economic assessment method, such as cost-benefit analysis. This amalgamation aims to combine different analytical frameworks, utilising the advantages found in both environmental and economic fields. This allowed for a detailed and comprehensive assessment of complex socio-environmental efforts.

The results of this study open a new debate on the possibility of revisiting the current dominant methods of economic assessment in the era of a circular economy. The necessity to replace environmentally damaging industrial practices with sustainable solutions. This poses the following questions: 1) Is the transformation of the current linear to intelligent and circular water systems necessary? 2) Is this transformation economically viable?

1.2. The main contributions

The installation and operation of most nature-based water solutions (NBWS) is relatively simple. However, assessing their economic, social, and environmental benefits and impacts is a complex process requiring many of variables, which is complemented with technical variables to understand their technological feasibility and applicability [14–17]. Until a decade ago, most engineering training programs did not consider environmental impact assessment in their curricula. There is a need for more realistic inclusion of environmental and social benefits and impact metrics in economic analyses. Despite their complexity, methods have recently been suggested to link environmental and social factors with technical variables to better describe the technological feasibility and applicability of NBS in water systems [14–17]. For example, Ghafourian et al. [15] offered a method to engage and receive input from stakeholders throughout Water Supply Chain Management (WSCM). This engagement results in a direct evaluation of the environmental and social benefits on the ground but also changes the approach and perspective regarding the wider economic benefits of NBS in WSCM.

The PSR model was developed by the Organization for Economic Cooperation and Development (OECD) and the United Nations Environment Program (UNEP) and is a recognized approach for the assessment of sustainability by specifying a number of performance indicators. The model connects the causes of environmental change (pressure) to their consequences (state) and programs, actions and policies (response) planned and enforced to respond to state changes [18]. The PSR process has been widely used as a tool for sustainability assessment in various fields [19–22]. A noticeable weakness in the PSR model is the absence of social and economic sustainability measure factors [23].

Cost–Benefit Analysis (CBA) is a widely recognized tool for economic evaluation and has been extensively applied to assess the economic feasibility of projects and technologies [6,24]. By expressing costs and benefits in monetary terms, CBA enables direct comparison between alternative interventions and supports decision-making based on economic efficiency. The method has also been employed to evaluate Nature-Based Solutions (NBS). For example, Feng and Hewage [25] applied CBA to assess the economic performance of green roofs across different markets by incorporating both private and public benefits.

Despite its usefulness, conventional CBA exhibits several methodological limitations when applied to Nature-Based Water Systems (NBWS). In particular, it may not adequately capture non-market ecosystem services, indirect environmental benefits, and the complex interactions between environmental pressures, system conditions, and management responses. Furthermore, CBA primarily focuses on monetised outcomes and therefore provides limited insight into the causal environmental processes that influence the long-term performance and sustainability of NBWS interventions. Consequently, while CBA can quantify economic efficiency, it may not fully reflect the broader environmental context within which nature-based interventions operate. To address these limitations, this study proposes an integrated Pressure–-State–Response and Cost–Benefit Analysis (PSR-CBA) framework. By combining the economic evaluation capabilities of CBA with the systematic environmental assessment provided by the PSR framework, the proposed approach enables a more comprehensive evaluation of NBWS technologies, linking environmental changes and management responses to their associated economic outcomes. The main contributions of this research are as follows: 1) Development of a novel PSR-CBA framework that integrates the environmental assessment capabilities of the Pressure–State–Response (PSR) model with the economic evaluation strengths of Cost–Benefit Analysis (CBA), enabling a more comprehensive assessment of NBWS performance. 2) Monetisation of environmental and social benefits, allowing non-market impacts and broader sustainability benefits associated with NBWS to be incorporated into economic decision-making alongside conventional financial indicators. 3) Application of the proposed framework to a water-scarce island case study, demonstrating the practical applicability of the PSR-CBA approach in evaluating nature-based interventions under conditions of limited water resources. 4) Provision of a decision-support tool for policymakers and practitioners, enabling a more holistic evaluation of NBWS investments by explicitly linking environmental pressures, system responses, and economic outcomes.

The remainder of this paper is organized as follows. Section 2 provides a context and an overview of the methodological approaches used in the literature. In Section 3, the research method based on the proposed approach is described. The results and analysis of the proposed approach applied to the case study are presented in Section 4. Section 5 summarises the findings of this study and provides suggestions for future research.

2. Background

Economic assessment of NBWS represents a critical frontier in environmental management, particularly when integrating holistic frameworks that capture both biophysical and economic dimensions of sustainability.

The integration of the Pressure-State-Response (PSR) framework with Cost-Benefit Analysis (CBA) provides a robust methodological approach for evaluating NBS. This combined framework emphasizes understanding causal-effect relationships while systematically valuing environmental and resource use costs and creating a foundation for informed mitigation. The complementary nature of these frameworks enables practitioners to address both the diagnostic (PSR) and evaluative (CBA) aspects of environmental management comprehensively. NBS implementation remains ostensibly sluggish, despite claims that it is more cost-effective and effective than gray infrastructure [26]. Literature identified a multitude of barriers, such as the absence of design standards, political reluctance, sectoral approaches to NBS, path dependencies, technological uncertainty, lack of funds, lack of economic models of NBS, inadequate institutional capacities, and the absence of a legal basis for enforcing NBS policy [11,27,28]. Among these barriers, the lack of economic models for NBS have recently attracted scholarly attention. NBS initiatives generate extensive public benefits, but do not generate immediate revenue streams sufficient to cover the substantial sunk costs they frequently incur [29]. To strengthen the economic case of NBS, researchers have adopted a business model approach, with the overarching objective of demonstrating how NBS creates value and identifying which economic models can convert this value into tangible cash flows ([29–31]; Ternell et al., 2020; [32]). A systematic review of peer-reviewed articles demonstrates that while NBS often involve higher initial capital investment, lifecycle cost analyses frequently report long-term savings, with median lifecycle cost differentials favoring NBS when maintenance regimes and co-benefits are included. This reveals a critical distinction: current assessment practices often overlook the superior economic performance of NBS over extended time horizons.

Ruangpan et al. [28] conducted an assessment of the effectiveness of NBS for flood risk management. When considering flood risk reduction alone, all considered NBS measures have higher costs than the benefits derived from avoiding flood damage; however, when incorporating co-benefits, several NBS have a net positive economic impact, with afforestation/reforestation and retention ponds yielding cost-benefit ratios of 3.5 and 5.6 respectively. B. V. Zanten et al., [33] Spatially explicit cost-benefit analysis frameworks reveal that benefit-cost ratios of mangrove conservation and restoration are found to be >1 in most districts, indicating positive social returns on investment, though mangrove conservation generally has higher benefit-cost ratios than restoration due to both higher implementation costs and the additional time required for restored mangroves to deliver ecosystem services. Incorporating ecosystem services into a Benefit-Cost Ratio analysis can raise the BCR from 1.46 to a range of 1.6–2.1, demonstrating the economic and environmental value of integrating NBS into urban planning (L [34]). Ghafourian et al., [15] applied Life-cycle cost-benefit analysis to assess the NBWS in Tinos Island and reveals that all the processes have Net present values exceeding zero, suggesting that incorporating co-benefits into economic assessments significantly enhances the economic efficiency and viability of NBS.

The Pressure–State–Response framework enables comprehensive evaluation of ecosystem health by assessing landscape pattern evolution, with results from application to the Luxi River Basin showing a shift in landscape patterns from relatively aggregated conFig. urations toward highly complex and fragmented ones, alongside substantial improvements in ecosystem health from initial deterioration to modest but stable improvement (Y [35]). R. Y. Sun et al., [36] by applying PSR framework with 14 distinct indicators revealed that Hubei Province exhibited mild ecological vulnerability from 2000 to 2023 but with a notable deteriorating trend, with extreme vulnerability areas expanding from 0.34% to 0.94%, while eastern regions demonstrate elevated vulnerability correlating with human activity intensity. Ratnaweera et al., [37] conducted a comprehensive review identifying monetary valuation gaps in regional and global cost-benefit analysis guidelines reveals an alarmingly low use of monetary valuation on socioeconomic and environmental impacts caused by water sector projects, highlighting the need for broader and more accessible recommendations for water-specific valuation methods.

The lack of economic models for NBS has recently attracted scholarly attention as NBS initiatives generate extensive public benefits but do not generate immediate revenue streams sufficient to cover substantial sunk costs. Recent studies demonstrate that researchers have adopted a business model approach with the overarching objective of demonstrating how NBS creates value and identifying which economic models can convert this value into tangible cash flows. A holistic framework to assess numerous co-benefits of NBS is missing, with the main objective being to overcome one of the main obstacles to NBS implementation: building a holistic assessment framework to measure effectiveness in terms of economic feasibility. Previous studies have primarily focused on economic assessment largely analysing the financing of implementation rather than economic impacts, leaving the economic impact of implementing NBS in the water sector ambiguous [38–40]

For example, Liquete et al. [38] carried out an ex-post assessment of the economic, environmental, and social benefits of a multi-purpose NBS for water pollution control in Northern Italy by accepting an ecosystem service approach and employing an integrated evaluation based on multi-criteria analysis. These authors emphasized that the approach has not yet been utilized, and in order to capture different aspects of NBS efficacy at different scales, more operationalisation and refinement are needed.

Despite substantial progress in developing economic models for NBS and specifily application of NBS in water system, significant methodological and implementation challenges persist. The integration of PSR frameworks with comprehensive cost-benefit analysis, while theoretically sound, faces practical obstacles including data availability, standardisation of valuation methods, and the challenge of capturing all relevant co-benefits within cohesive analytical frameworks.

A review of the existing literature reveals several significant research gaps in the assessment and implementation of Nature-Based Solutions (NBS). (i) There is a notable lack of comprehensive economic assessment frameworks. To date, most studies have concentrated on technical performance and environmental benefits of NBS, while widely adopted sustainability assessment approaches including the Sustainability Assessment Protocol, Life Cycle Assessment (LCA), Ecological Footprint Analysis, and the Pressure–State–Response (PSR) framework has provided only limited consideration of economic dimensions. (ii) Although the growing body of literature on NBS business models seeks to demonstrate value creation and identify mechanisms through which such value can be translated into revenue streams, these studies predominantly focus on financing and investment strategies for NBS implementation. Consequently, insufficient attention has been given to the systematic evaluation of the broader economic benefits and impacts generated by NBS interventions. (iii) Research examining the application of NBS within water systems remains relatively scarce. This limited sector-specific focus has resulted in considerable uncertainty regarding the economic implications and long-term value of implementing NBS in water-related infrastructure and management systems. Addressing these critical knowledge gaps is essential to overcoming one of the principal barriers to the wider adoption of NBS in the water sector: the lack of robust evidence demonstrating their economic viability and value. Accordingly, the primary objective of this study is to develop a holistic assessment framework that integrates the Pressure–State–Response (PSR) approach with Cost–Benefit Analysis (CBA) to evaluate both the feasibility and economic performance of Nature-Based Water Systems (NBWS). By combining environmental and economic assessment perspectives. The proposed framework provides a comprehensive decision-support tool capable of quantifying the economic benefits associated with investments in NBS for water systems, thereby enabling more informed and evidence-based policymaking and investment decisions.

3. Materials and methods: the proposed approach

3.1. State of the art

In the agricultural sector, an innovative, nature-inspired rainwater harvesting system in a secluded agricultural area was proposed. In addition, the cultivation of oregano crops results in increased biodiversity. An effective NBS irrigation system was implemented by constructing a shallow subsurface rainwater collector designed to drain rainwater into two cylindrical storage containers. The oregano crop is irrigated with precision irrigation, and the harvest is processed to produce essential oils, thereby adding value to the entire supply chain, which will be exploited locally. The system is intended to solve the following issues: i) the availability of low-cost water in areas lacking any other water source and ii) creating a business proposal for the production of essential oils. The conventional (base) and NBWS (case) scenarios are shown in Fig. 1.

3.2. Case study and system specification

A case study was selected as part of the "HYDROUSA" H2020 project. This case study is based on Mykonos Island in the Eastern Mediterranean

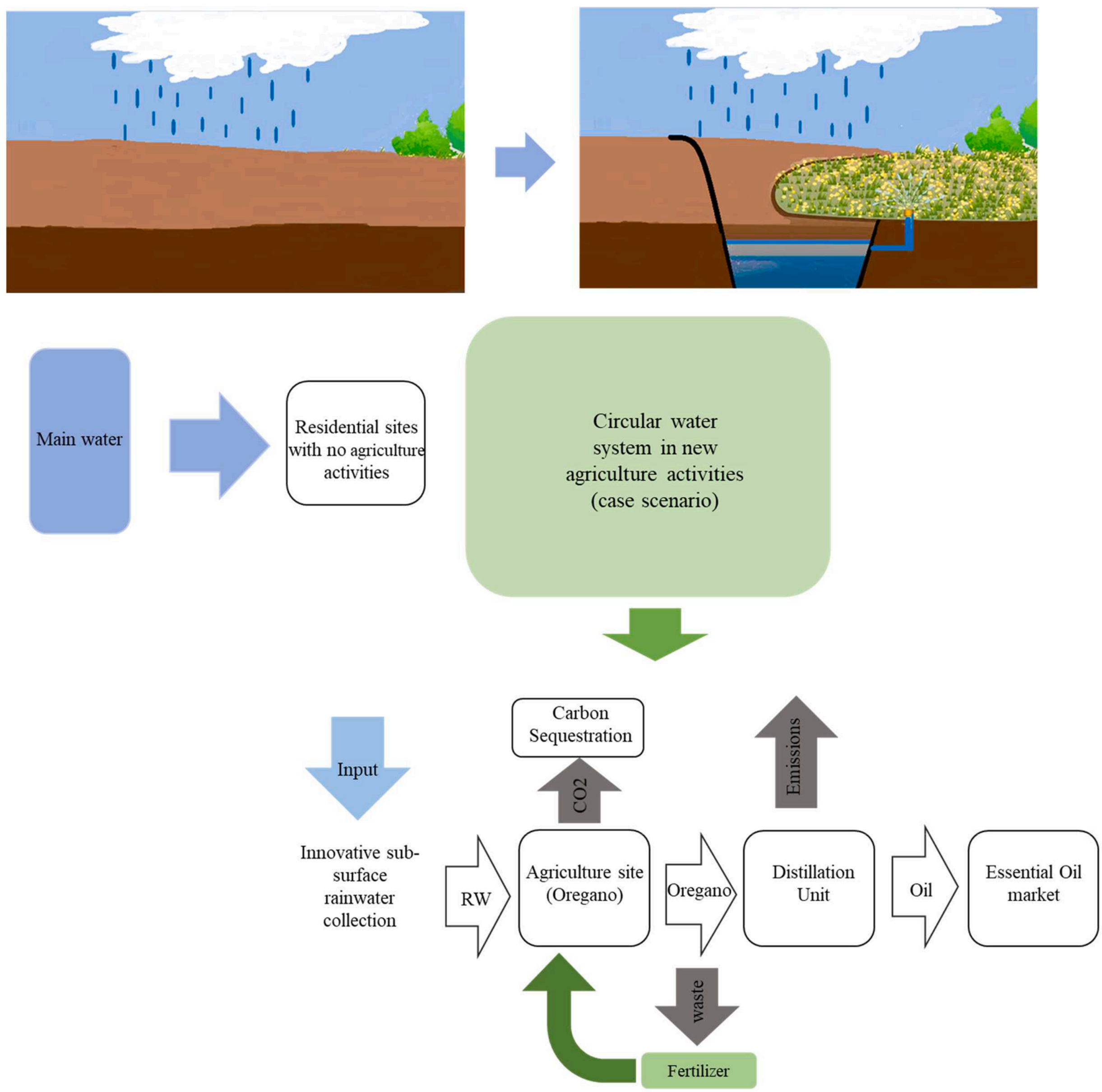

Fig. 1. The conventional (base) scenario and NBWS (case) scenario NBWS in Mykonos Island.

region. The area and population of Mykonos are approximately 87 km^2 and 10,000 permanent residents, respectively, with an annual rainfall of 350 mm. The island is a well-known tourist destination, with a total of three million visitors in 2020 [41]. Due to limited surface water resources and rainfall, Mykonos partly relies on unconventional water resources for its water needs (i.e., five desalination plants) and mainly on conventional water resources (two water reservoirs, drills, and private wells). The drinking water supply comes from two reservoirs, and most of the irrigation demand is fulfilled by private wells.

Two scenarios, the current linear system and circular case, are specified. The base case is a conventional water system; and because of the inadequate water resources in this area, agricultural activity does not take place, and no circular system is implemented. Therefore, we assume that the cost and benefit in this case is zero.

The circular scenario aimed to address the island's severe water shortages by developing new economic activities in Mykonos. The water loops implemented in HYDRO3 include rainwater collection and the local irrigation of oregano plants. The Greek government provides a 50% grant for the implementation of rainwater harvesting and irrigation systems. This shallow, subsurface rainwater collection system comprises a geomembrane at the bottom to prevent water from penetrating into the soil and a geotextile at the top to enable water but not soil to pass through. The entire structure was covered with sand to prevent intrusions. The rainwater collection system covered 200 m^2, allowing for the collection of >50 m^3 of rainwater per year. The collected rainwater will irrigate 0.4 ha of oregano cultivation. Oregano was chosen because it can thrive on the local climate and requires little water. The harvested oregano is transferred to a nearby steam distillation machine where the essential oil is extracted and sold in the local market. The closed water loops provide a self-sufficient system with the following specifications: (i) no external water supply is required to cultivate 0.4 ha of oregano, (ii)production of essential oil, (iii) job maintenance in this area, and (iv) environmental benefits due to atmospheric carbon sequestration. The specific energy (electricity) needs for all activities were set at 141.2 kWh/year based on data from the monitored site and on-site measurements. The current calculation uses a fixed price of 0.21 €/kWh for electricity in Greece, as of March 2022. Fig. 2 shows a water flow schematic for the rainwater system, CAPEX, and OPEX, which are

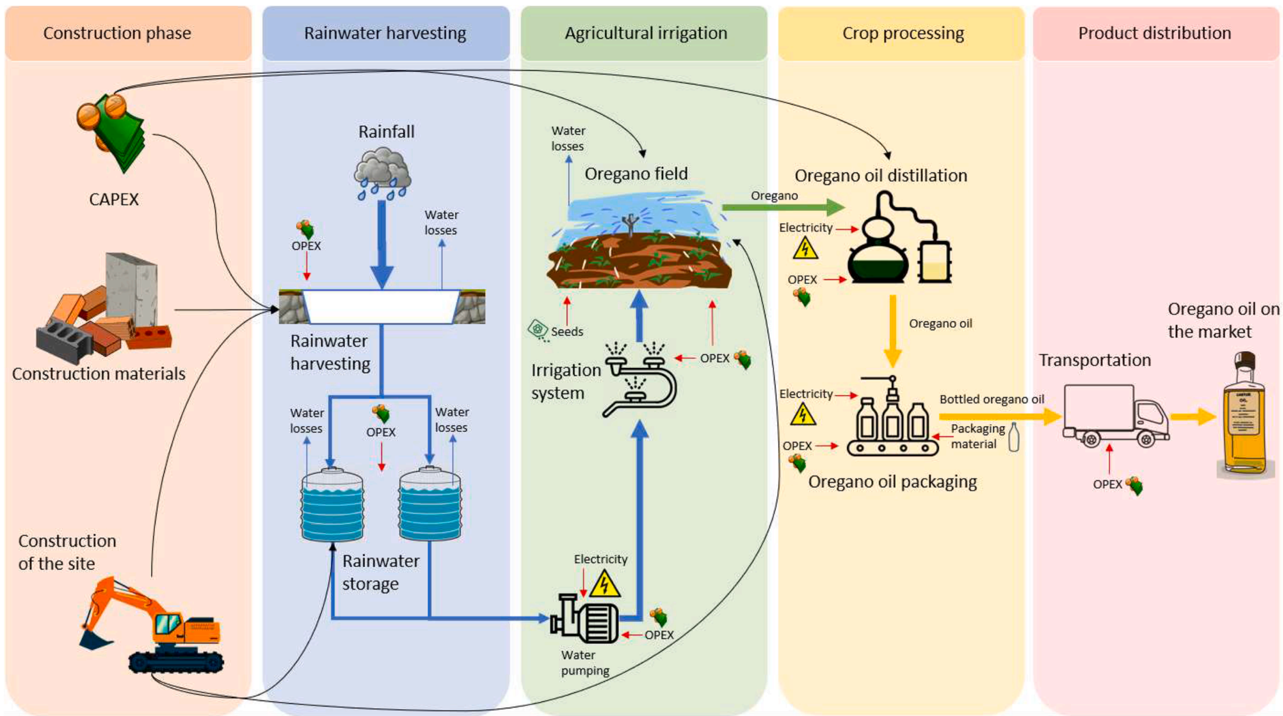

Fig. 2. System conFig. uration of CWS.

required to implement and operate this system in Mykonos. Material and energy inventory of RWH in Mykonos per functional unit is presented in Table 1 in supplementary material.

3.3. System boundary and data requirement

Fig. 3 shows the boundaries of the NBWS system. For the circular case, CAPEX, OPEX, economic benefits, and environmental and social benefits were calculated. The assessment only includes the value of extra materials and the energy required to modify the current water system to an RWH system.

The system boundaries of the circular case comprise the material, processing, and manufacturing of products. The literature shows that the transportation of goods from one location to another, and recycling, landfilling, or incineration of waste had no impact on economic results [24,42]; therefore, these stages were excluded from this study. Moreover, the following seven parameters are included in the operational and maintenance stage: (i) Total electricity usage, (ii) Renewing annual organic certification (iii) Cost of packaging the essential oil (iv) Fertilizer use (v) and Consumables Certification & Product Packaging

Table 1
Classification of indicator and related sub-indicator for HYDRO3.

Components	Principles	Indicators	Means of calculation	Unit
Pressure	Water Security	Water losses	*Amount of water wasted comprise leakage from pipes, joints and fittings, from leaking reservoir walls, and from reservoir overflows*	m^3/year
	Climate change	Carbon footprint (CO_2)	*Business operation as normal* Emission factor*	kg
State	Water Scarcity Index (WSI)	WSI	*Total annual freshwater withdrawal/ Total available freshwater*	%
	Ecosystem Integrity Index (EII)	EII	*The spatial distribution and change of the vegetation cover (ecosystem condition indicators)*	%
Response	NBWS	Cost	*CAPEX+OPEX*	€/year
		Benefit	*Internal Benefit+ External Benefit**	€/year

*Explained and detailed in Table 4.

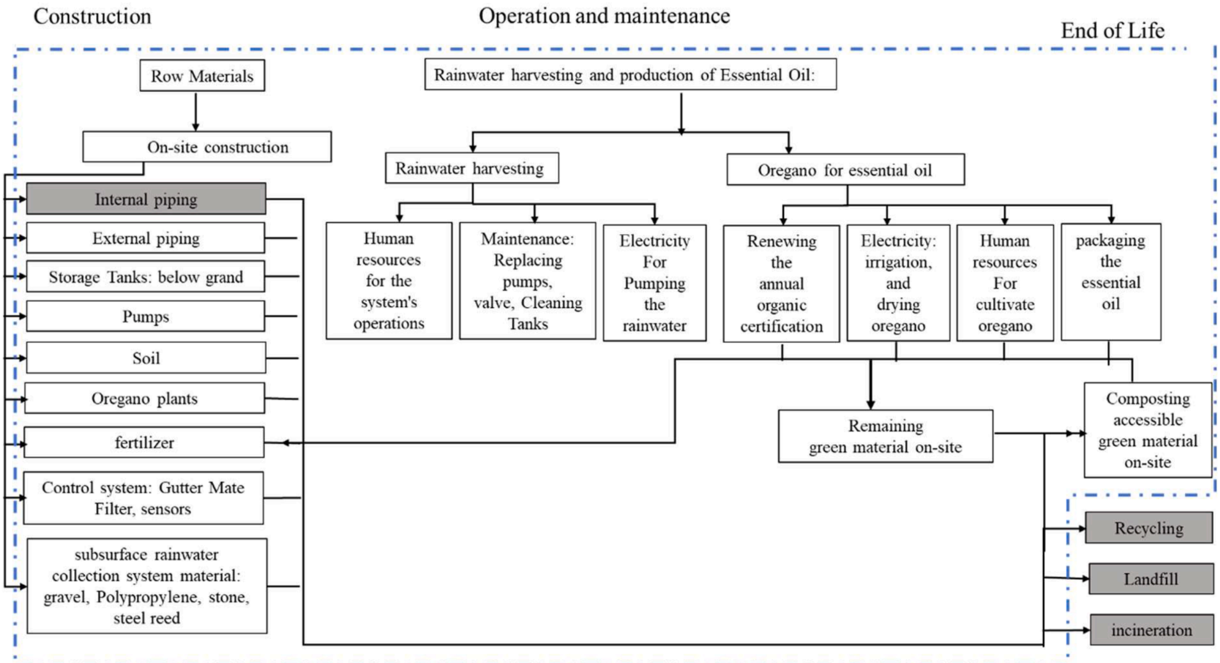

Fig. 3. System Boundary of NBWS in Mykonos.

The following benefits have also been considered during the operational stage: (i) essential oil sale, (ii) environmental benefit from carbon sequestration due to oregano cultivation, (iii) contribution to the (local) economy, and (iv) benefit from selling hydrosol.

3.4. Proposing an inclusive economic assessment based on PSR and CBA

A three-step iterative process was proposed. Step (1) calculates the sustainability index score using PSR for the NBWS transition. Step (2) aligns the acquired data with the performance of the system using the CBA framework. Step (3) Translate the output into a simple actionable recommendation (decision-making) by creating a comparative set of results. The proposed approach and its associated stages are shown in Fig. 4.

The proposed approach integrates the PSR approach and CBA, taking into account environmental, social, and economic indicators. This may lead to a more inclusive and realistic economic assessment of the NBWS.

The water system is subject to a variety of pressures, which alter the state of resource usage and compel humans to respond to and manage the system. The PSR model focuses on the connection between resource-environmental stresses and resource-environmental degradation. The first step is to analyse the pressure and state the common indicators to understand whether a response in a specific area with water scarcity is required. Pressure and state indicators are generic environmental indicators that reveal the overall environmental performance of the case study. The second step assessed whether the response was economically

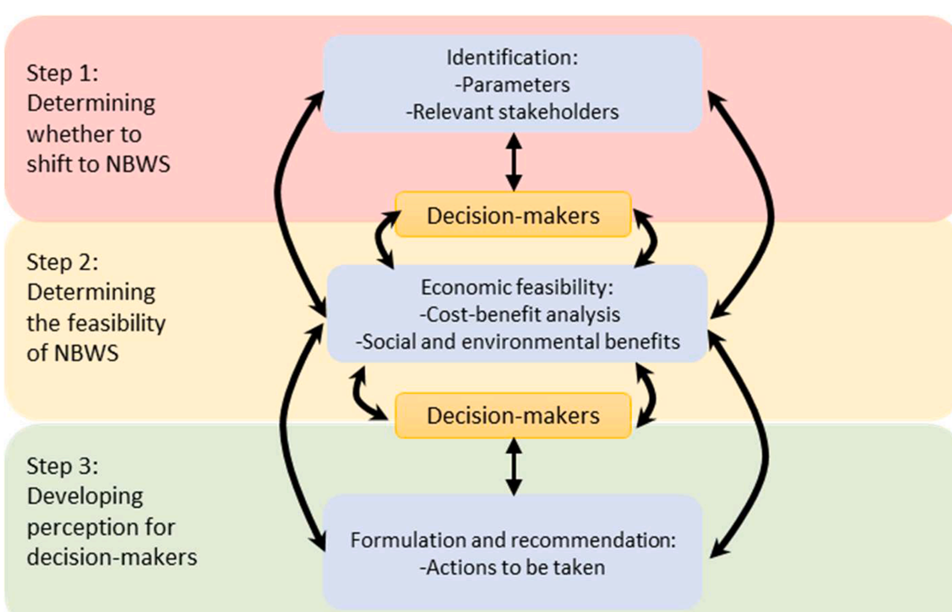

Fig. 4. Proposed Approach and its Associated Stages.

feasible. The third step involves generating the necessary knowledge and insight to develop recommendations.

To perform the first step of the assessment the state indicators, which represent the current water condition of the island affected by the environmental pressure, are examined using urban scale data to confirm the need for response. In the second step, a CBA is carried out, which considers quantitative values of internal and external costs and benefits of the response to determine whether the response is economically sustainable and whether the response contributes to pressure mitigation. The results of this process provide the foundation for making decisions that are more likely to lead to sustainable outcomes.

3.4.1. Step 1: pressure-state-response (PSR) approach: selection of indicators to be fit in PSR approach

To select these indicators, the evaluation, diagnosis, and comparison of Mykonos island-relevant generic indicators were considered. The first set of indicators examines the pressure on the island's water resources and can be applied to any climate-matched, water-scarce location. The two pressing issues on Mykonos Island are climate change and water security, which increases the pressure on the state of the environment and water resources, making water scarcity one of the biggest problems on the island [41]. Consequently, two indicators related to climate change and water security for which data are available for Mykonos Island were selected at the pressure side. The concentration of carbon dioxide (carbon footprint) has been used as an indicator for evaluating climate change criteria [43]. Owing to the availability of data for Mykonos Island, water loss was selected as the water security indicator, Due to the absence of a rainwater collecting system in the conventional system, rainfall is not effectively managed, resulting in water loss. Direct and indirect GHG emissions were considered for the carbon footprint, and an assumption was made with respect to atmospheric CO_2 sequestration by oregano plants due to lack of data and to reduce uncertainty. Atmospheric CO_2 sequestration was assessed according to the amount of carbon in the harvested plant, because the amount of carbon absorbed aboveground and underground during the cultivation stage was not measured yet. Therefore, the absorbed CO_2 by the plants was underestimated. The CML-IA impact model was used to assess the Global Warming Potential over 100 years. The CML-IA was developed by the Centre of Environmental Science of Leiden University and calculates midpoint impact indicators [44]. The Global Warming Potential calculation was based on the characterization model developed by the IPCC (IPCC, 2013) to convert GHG emissions to kg of CO_2 eq [45]. State indicators describe the conditions of the water and its resistance to pressure-induced changes. Two indicators that reflect the state of the environment under the influence of climate change and water stress were chosen. Due to the availability of water data, the Water Scarcity Index (WSI) was chosen to analyse the water deficit. Regarding the effect of climate change, the Ecosystem Integrity Index (EII) was chosen because it is pertinent to this study and is a comprehensive, unique, robust, and simple index to assess and monitor the condition of a specific ecosystem under climate change, based on an optimal state that must be established for the ecoregion [46]. The third set of indicators refers to the response mechanisms that are usually achieved through the direct actions of governance, decision-makers, and society in the development or adoption of improved water management systems. In this study, the implementation of NBWS was a response to mitigate or eliminate environmental pressure, as measured by the cost-benefit indicator. The PSR approach was used to validate the selected indications, as shown in Fig. 5. The components, concepts, chosen indicators, and calculations are listed in Table 1.

3.4.2. Stage 2: economic assessment of response applying Cost- benefit analysis (CBA)

The direct and indirect costs and benefits are both taken into consideration in the cost and benefit analysis. In terms of quantitative value, the direct costs that are incurred are CAPEX and OPEX. It is possible to greatly reduce or remove the pressure that is placed on the environment by utilising NBWS to gather and utilise rainwater for agricultural purposes (oregano cultivation). Water losses, which in this case refer to rainwater that is not used and is squandered to the environment, are the pressure that is placed on the environment. Due to the fact that these data are deemed to represent indirect benefits associated with NBWS, they have been assigned a "negative cost value" in comparison to the base case (baseline scenario) in which there was no NBWS. A negative cost value of water loss indicates that it is prevented and recorded as an indirect benefit known as "avoided water loss" as a result of NBWS implementation. Both the release of nitrous oxide from agricultural soils and the release of methane from manures are the two most significant sources of greenhouse gases that are produced by agriculture. These two sources contribute to the totality of indirect costs,

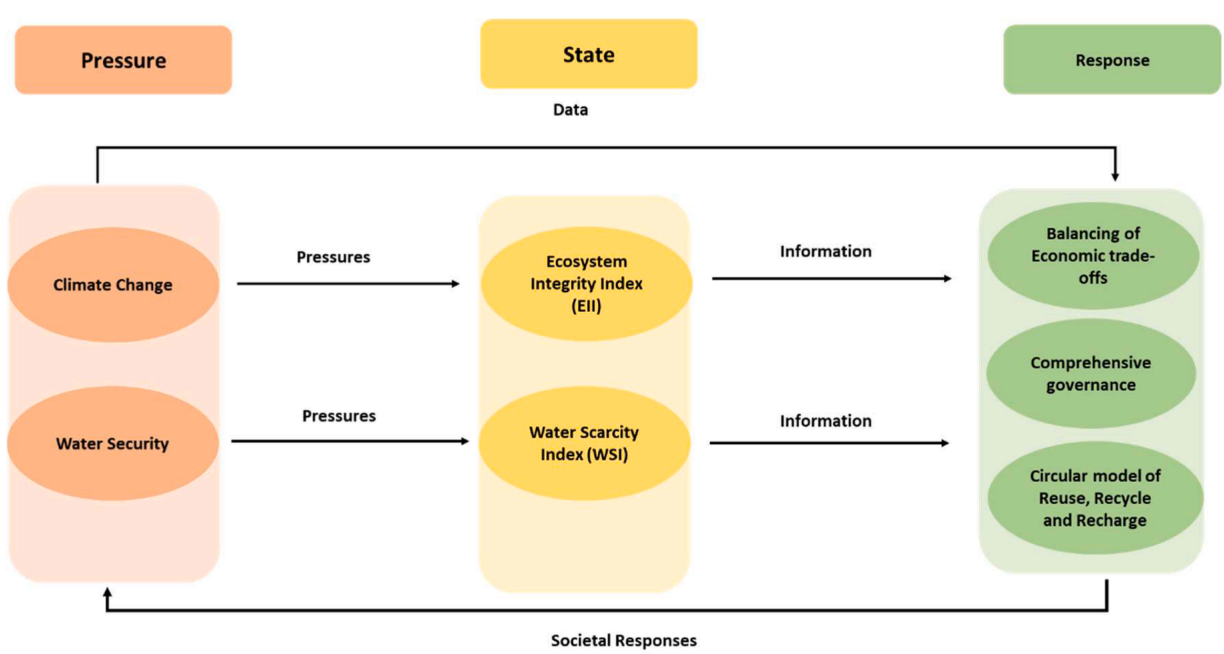

Fig. 5. Indicators that fit the NBS and water management concept.

which are presumed to be zero. This is due to the fact that positive carbon sequestration is accounted for as an indirect benefit; the method for calculating carbon sequestration and converting it to monetary value is described in the following section. Contribution to the economy is the parameter that shows the adoption of NBWS adds value to Greece's performance, as measured by gross domestic product (GDP). The difference between GDP with and without NBWS was used to determine the added value to the local economy. The percentage of local economy impact on GDP is the coefficient of this difference in GDP. Although the indicator "contribution to economy" primarily reflects economic benefits, it also contributes indirectly to the social dimension of sustainability. By stimulating local economic activity, generating employment opportunities, and improving household income, NBWS can enhance community well-being and socio-economic resilience. Nevertheless, owing to the limited availability of data at the time of the study, other important social benefits, including improved water security, reduced health risks, and enhanced community participation, could not be explicitly quantified. The sale of essential oil and hydrosol is the direct benefit of NBWS operations that are stated in monetary value. To differentiate and highlight the significance of incorporating environmental and social parameters into the proposed model, the CBA is computed exclusively based on direct costs and benefits (which already possess monetary value). It is evident that a more precise feasibility assessment of nature-based solutions can be achieved by translating additional social and environmental costs and benefits [15], despite the fact that this study only considers three indirect costs and benefits due to a lack of data Fig. 6.

The Total cost (TC) is calculated based on the approach developed by Ghafourian et al. [24], called life cycle cost-benefit shadow pricing (LCCBS), and is shown in Eq. (1):

$$TC_i = CX_i + \sum_{t=1}^{T} \frac{(OMC_I + OMC_E)_{i,t}}{(1+r)^t} \tag{1}$$

Where $CX_i$is the capital cost (€) of item i; $OMC_{i,t}$ is the maintenance and operational costs (€) for t years after installation of item i; T is the lifespan of the project, and r is the yearly discount rate (%). The majority of the constructed components (e.g., pipelines, storage tanks) are expected to last longer than 20 years and will not need to be changed within this timeframe. Therefore, a life span of 20 years and Greek real discount rate of 6.1% were considered in this study.

The Total benefit (TB) was calculated using Eq. (2).

$$TB_I = \sum_{t=1}^{T} \frac{(B_I + B_E)_{i,t}}{(1+r)^t} = \sum_{t=1}^{T} \frac{[(AR_t * PR_t) + (AO_t * PO_t) + \ldots + (AB_t * PB_t)]}{(1+r)^t} \tag{2}$$

where B_I= internal benefit (€); $\mathbf{B}_E$ = **external benefit** (€); AR_t= annual harvested rainwater volume (m^3); PR_t: the market value of water (€/m^3); AO_t= annual produced essential oil (m^3); PO_t: the market value of essential oil (€/m^3); AB_t = annual external benefit (Unit); PB_t: the market of external benefit (€/unit).

The environmental benefits linked to carbon sequestration and the societal benefits resulting from contributions to the economy are both included in the external benefits of this study. The FAO EX-ACT (Ex-ante Carbon Balance Tool (EX-ACT) calculates the effects of land-use change on GHG emissions and carbon sequestration ex ante. EX-ACT depicts the impact of agricultural and forestry activities using carbon footprint as a measure of climate change mitigation. EX-ACT was used to calculate the amount of carbon that could be sequestered by various natural and inspired solutions (Table 5 of supplementary material).

3.5. Economic indicators

Three economic indicators were used: the Modified Internal rate of return (MIRR), net present value (NPV), benefit-cost ratio (BCR), and payback period (PP). A project with a positive NPV and PP less than the project's life span and a high MIRR is feasible [47]. MIRR, NPV, BCR, and PP are calculated using Eq. (3), (4, 5), and (6) respectively.

$$MIRR = \sqrt[n]{\frac{FVCF_t}{PVCF_t}} - 1$$
$$MIRR = \sqrt[n]{\frac{FV(Positive\ CF_t * \ Cost\ of\ capital)}{PV(Initial\ outlays * Financial\ Cost)}} - 1 \tag{3}$$

Where $FVCF_t$ is the future value of positive cash flow at the cost of capital for the project and $PVCF_t$ is the present value of negative cash flows at the financing cost of the project and n is the number of years of project. total cash flow; C_0=CAPEX; t = years; r= discount rate

$$NPV = \sum_{t=0}^{10} \left[\frac{(TB_t - TC_{t)}}{(1+r)^t}\right] \tag{4}$$

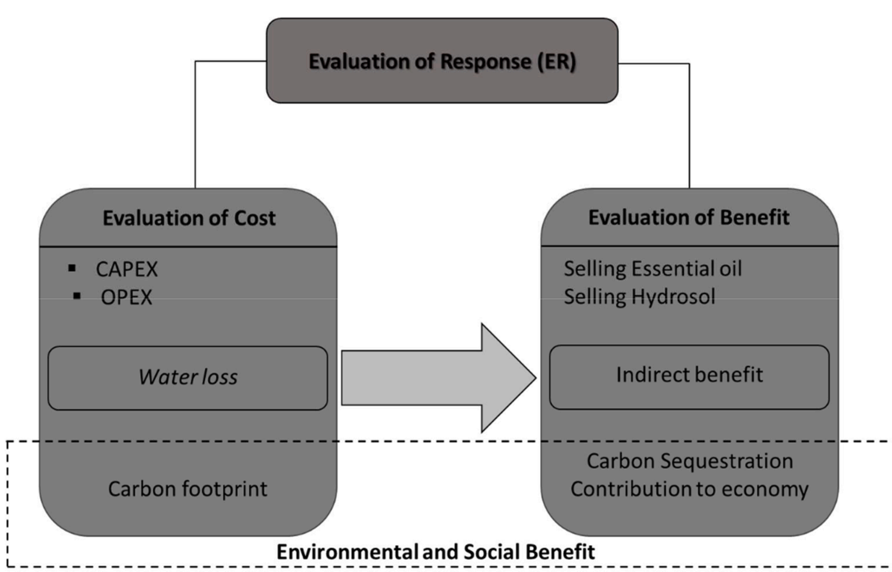

Fig. 6. Cost-benefit analysis component.

Where TB is the total benefit, TC is the total cost, and r is the discount rate.

$$BCR = PV\left[\frac{(TB)}{(TC)}\right] \tag{5}$$

Where PV is present value of [(TB)/(TC)], TB is the total benefit and TC is the total cost.

$$PP = \frac{CAPEX}{yearly\ revenues - OPEX} \tag{6}$$

If the NPV is negative, the BCR is <1, or the PP is not present in the life span of the project, the project is considered not economically viable.

4. Sensitivity analysis

A sensitivity analysis was performed to simultaneously assess the variation range of all input parameters in the proposed model. This aids in detecting variations in the expected target. In the process of decision-making, unlike other indicators, NPV tell you how much money a project might make. Therefore, in this study, a sensitivity analysis is performed on the NPV to determine how the profitability of a certain NBWS will be affected by changes in its input variables. A stakeholder may wish to know how favourable or unfavourable conditions may affect the profitability based on What if Scenarios. A sensitivity analysis using local graphical methods was performed on the NPV correlated with a change in economic influential factors, including CAPEX (€), cash flow (€/year), discount rate (%), and water tariff (€/m3) that already are in quantitative value. Once the improvements in the overall benefit have been examined, it will be possible to determine the project's robustness or true feasibility. The sensitivity analysis of the NPV based on economic parameters could be a key consideration for companies to anticipate future events due to changes in economic parameters.

5. Results and discussion

5.1. Assessment of pressure and state index

To conduct the first step of the feasibility study, pressure and state index data were collected. In the subsequent part, when a full economic evaluation is conducted, pressure indicators such as water demand and water loss are analysed as avoided pressures under the NBWS implementation. State indicators for base scenario are general indicators that are linked to a specific urban area, and the data associated with them can be found in standard databases. Data related to the Water Security index (WSI) and Ecosystem Integrity Index (EII) were collected from the World Resources Institute (WRI, 2021). As follows:

$$\text{WSI}:\ 0.88 \text{ and},\ \text{EII} =\ 6.6$$

According to WRI (2021), water stress above 80% is classified as extremely high, and EII below 8 is classified as low to medium integrity.

$$\text{WSI} =\ (>80\%):\ \text{extremely high} - \text{water stress}$$

$$\text{EII} =\ (<8):\ \text{with low to medium Ecosystem integrity}$$

This result confirms that a response is required to overcome the environmental pressure. The issue now is to understand whether the response of the transition to an NBS is economically feasible. To evaluate the system from an economic perspective, a cost-benefit analysis was performed, as described in the following section.

Global Warming Potential (GWP) results can be classified into indirect emissions and CO_2 capture in a case study. Greenhouse gas emissions are released mainly not at the location of the case study but due to the generation of electricity and materials that are used at the farm and distillation and packaging stages. In contrast, oregano cultivation results in CO_2 absorption during the growth phase. The quantity of absorbed CO_2 absorption and greenhouse gas release were comparable, which resulted in a carbon footprint of 35 kg of CO_2 during one year of operation (Table 2).

5.2. Economic feasibility assessment of NBWS

Based on the data from the implemented NBWS in HYDRO3, the total harvested rainwater was approximately 66.79 m^3/year. Table 3 summarizes the capital, installation, and annual operating and maintenance expenditures of the NBWS implemented in Mykonos. The data are received from partners as well as information from HYDROUSA demonstrator site-local standards (because the amount of fertiliser that will be used is equivalent to the amount of fertiliser produced from green residual waste, it is omitted from the calculation). Table 4 presents all internal and external benefits of implementing HYDRO. The Greek government provides a 50% grant for the implementation of rainwater harvesting and irrigation systems. Consequently, the capital expenditure (CAPEX) associated with these systems is halved in the CAPEX calculation. Therefore, the CAPEX for NBWS is 14,330. Given that the baseline scenario represents the current state of the system, with an estimation that the cultivation of Oregano is taken place with a linear water system. Therefore, the capital expenditure (CAPEX), operating expenditure (OPEX), and revenue are presented in Tables 3 and 4. The estimation is that in both scenarios we have a same amount of oregano and hydrosol.

The economic benefit listed in Table 4 has a specific market value; therefore, it is calculated by multiplying the quantity by the unit market price. The environmental benefit of carbon sequestration is estimated as 1.47 (T/year), in line with the Ex-ACT method from FAO - Cost of carbon [48]. Based on a World Bank report on the State and Trends of Carbon Pricing, 2020, the EX-ACT Tool estimates the monetary quantification for unit price in the range of 41.5 to 81 €/t, which is the target value for the Paris Agreement [49]. In this study, 51 €/t was considered, which corresponds to the average agreed-upon price range. The supplementary material contains the detailed calculation method. The indirect benefit in this study is the pressure on the environment that is addressed by implementing NBWS, as the water demand is fulfilled by harvested rainwater, transition to NBWS helps to eliminate the amount of water wasted by leakage from pipes, joints, and fittings; thus, these are counted as indirect benefits. According to Ormond [50], the use of different forms of oregano can reduce the carbon footprint by 24%. Therefore, 24% of 1.48 T carbon was used in this study as the value of the avoided carbon footprint.

Based on the data in Tables 3 and 4 and using Eq. (3), (4), and (5), the economic indicators NPV, MIRR, BCR, and PP were estimated and are shown in Table 5.

Taking into account the environmental and social benefits, as shown in Table 5, the system is more appealing from an economic perspective to implement. This is demonstrated by the fact that the system is more desirable.According to the findings of the four economic indicators, the transition to NBWS is economically feasible. Because the NPV is positive, the BCR is greater than 1, and the PP is approximately six years, which is within the project's lifespan. When the MIRR exceeds the investor's required rate of return, which is typically greater than the discount rate, it is expected that the investment will generate profit. Furthermore, the results for all indicators demonstrate an intriguing point: despite the circular water scenario having a higher CAPEX, it remains a more

Table 2

Carbon footprint and kg of CO_2 eq. due to CO_2 capture and indirect emissions in one year of operation.

Damage category	Unit	Total
Global warming potential (carbon footprint)	kg CO_2-eq	35.06432
CO_2 capture by the plants	kg CO_2-eq	110.7332
CO_2 emissions of the system	kg CO_2-eq	145.7975

Table 3
Cash flow of implemented NBWS in Mykonos (HYDRO3).

Specification	Type of Cost	Unit	Case scenario (NBWS)
CAPEX	Rainwater harvesting	€	17,500.0
	Agriculture	€	1630.0
	Irrigation system	€	3700.0
	Drying	€	0.0
	Distillation	€	1100.0
	Packaging	€	0.0
	Other (legal affairs, certifications, etc.)	€	1000.0
	Total	€	**24,930**
	Total with considering the government grant	€	**14,330**
OPEX	Costs for water (distillation)	€/year	4.6
	Costs for energy	€/year	17.9
	Costs for fertilizers	€/year	3.2
	Consumables, Certification & Product Packaging	€/year	530.0
	Total	€/year	**555.6**

* Human resources at present and in this specific case work as volunteers at no cost, although this may change if the system is profitable.

Table 4
The total (direct and indirect) benefits of HYDRO3.

Benefit Aspect	Benefit	Level (case)	market Value	Unit	Total Benefit-Case scenario (circular-NBWS)
Economics	Sale of essential oil produced from oregano	400 (bottle of 5 ml)	16 (€/each bottle)	€/year	2882
	Sale of hydrosol	20 kg	54 (€/kg)	€/year	486
Environmental	Carbon sequestration - €/year	1.47 (T/year)	41.5 (€/T)	€/year	61.01
Social	Contribution to economy	181,675 (GDP)	32,701 (GDP due to tourism)	€/year	1564
Indirect benefit coming from Pressure mitigation	Avoided water loss	62.1 (m^3/ year)	1 (€/m3)	€/year	62.1
Total				**€/year**	**5055.11**

Table 5
Economic Indicators.

Economic indicator	Net Present Value (€)	Modified internal rate of return (%)	Benefit-Cost ratio	Payback Period (Year)
Value (Direct and indirect cost and benefit)	€ 30,905.52	13%	6.2	3.18
Value (only direct cost and benefit)	€ 14,342.23	4.80%	3.77	5.1

feasible undertaking compared to the linear system. Also, an additional assessment indicated that the project remained economically viable in the absence of the 50% capital subsidy, although the subsidy improved the overall economic performance.

5.3. Sensitivity analysis

In the present study, a sensitivity analysis is undertaken to evaluate the influence of alterations in economic parameters on the Net Present Value (NPV). The study designates the Net Present Value (NPV) as the dependent variable, while considering water tariffs, discount rate, CAPEX, and cash flow as independent variables. The annual cash flow was calculated as the difference between revenues and OPEX (Cash Flow= Revenue- OPEX); therefore, variations in cash flow implicitly capture the effects of changes in OPEX on the NPV. A change of ±20% was applied to each of these economic parameters. Fig. 7(a) depicts the outcomes of the sensitivity analysis with respect to alterations in water tariffs. The observed linear increase in NPV underscores the positive correlation between the financial viability of the NBWS and escalating water tariffs. Fig. 7(b) shows the findings of the sensitivity analysis concerning the variations in the discount rate. The linear decrease in NPV with an escalation in discount rate signifies an improvement in the financial feasibility of the NBWS when the discount rate diminishes. Furthermore, Fig. 7(c) illustrates the results of the sensitivity analysis associated with alterations in annual cash flow, which reflects the combined effect of revenues and operating expenditures (OPEX). Fig. 7 (d) provides insights into the sensitivity analysis with a 20% change in CAPEX and its subsequent impact on the NPV performance. The observed linear decrease in NPV with an elevation in CAPEX reveals that a CAPEX exceeding $29,430.29 is economically unviable, assuming that all other factors remain constant.

Upon analysing the Fig. ure and performing average rate of change calculations, it was determined that there was a ± 20% change in all these factors, resulting in a different corresponding change in the NPV. As a ± 20% change in water tariffs changes the NPV by .65%, the alteration in the variables r, cash flow, and CAPEX results in a corresponding variation in the NPV, with 12%, 3%, and 11%, respectively. This indicates that the NPV result is highly sensitive to changes in the discount rate but is less affected by variations in water tariffs. These findings underscore the high sensitivity of the NPV to changes in the discount rate, emphasizing its pronounced impact on financial outcomes. Conversely, variations in water tariffs have a comparatively lower influence on NPV. The results of this sensitivity analysis provide valuable insights into the intricate dynamics of economic parameters and their consequences on the financial viability of the NBWS

6. Conclusions

The transformation of industry and specific NBWS is necessary and imminent. However, what remains to be addressed is the solid economic argument for such a fundamental commitment and change in industry attitude. In order to create a more comprehensive economic valuation of NBWS, the PSR-CBA approach was proposed. This approach provides insights for decision making. The solution seems to be effective in addressing the most pressing concerns in water management if an intervention by policymakers in the current water system is necessary and if such an intervention is economically feasible.

We anticipate that the proposed method will facilitate debate regarding the involvement of policymakers in modifying rules and guidelines to advance sustainable water systems. Furthermore, by converting the environmental benefits and losses into monetary terms in the proposed model, a broader range of stakeholders may be engaged in making crucial decisions about investment and the advancement of current intelligent and nature-based solution technologies.

Internal and external costs and benefits were considered, and the quantitative value of the environmental and social cost impact that was reduced or eliminated as a result of NBWS implementation was also considered as a benefit. This study evaluated the economic viability of an NBWS on the Greek island of Mykonos. The result for all indicators calculated for NBWS once without considering the indirect cost and benefit and second time incorporating indirect cost and benefit. the

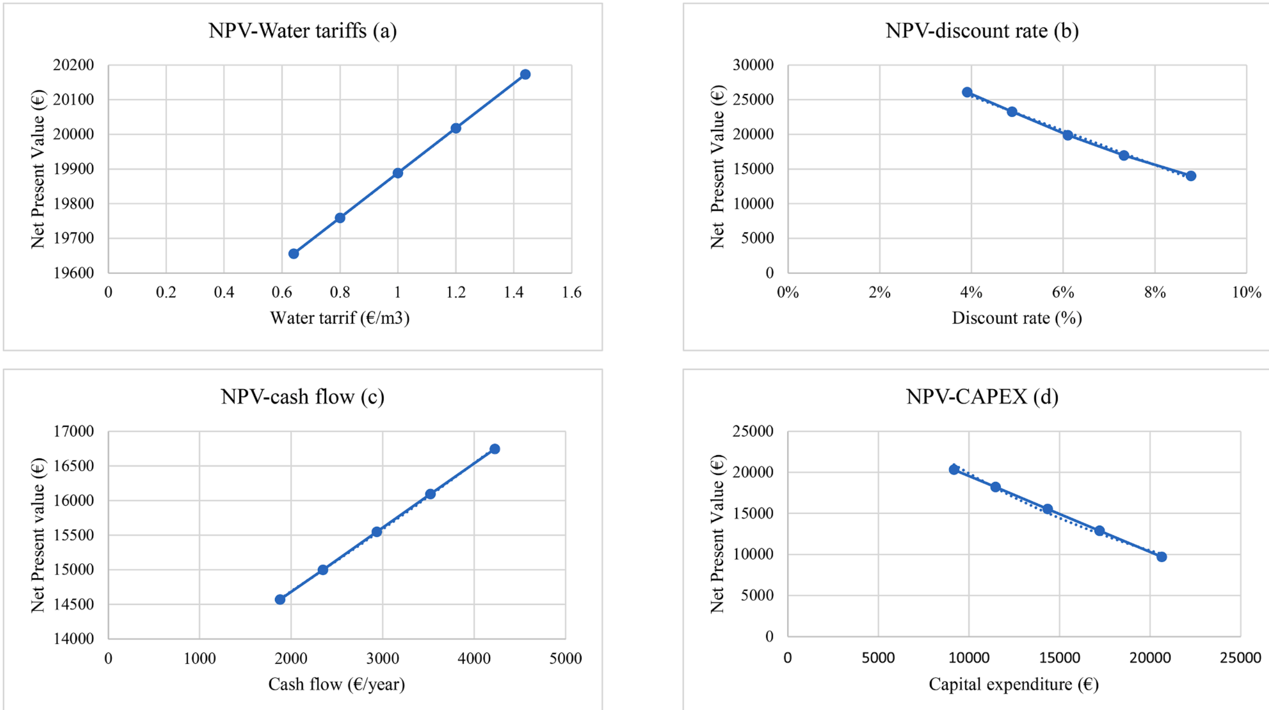

Fig. 7. Sensitivity analysis for NPV with respect to water tariff (a), discount rate (b), cash flow (c), and CAPEX (d).

latter continues to be a more viable undertaking in comparison. This can be explained by the environmental and social benefits associated with the circular scenario, which are quantified in monetary values. The developed economic assessment methodology can provide an accurate and realistic evaluation of NBWS economic performance, according to the findings of this study. The results of this economic analysis confirmed that the application of the proposed methodological approach provides key stakeholders with insightful information regarding key identified factors, such as the environmental and economic viability of the planned NBWS. Therefore, it is hypothesised that the proposed approach can provide policymakers with a better understanding of the deployment and scaling up of these technologies to meet their objectives, although additional research is required to confirm this assertion.

This study is subject to several limitations that should be considered when interpreting the results. First, the analysis was constrained by the availability of technical, environmental, and economic data for Nature-Based Water Systems (NBWS), particularly long-term operational and maintenance data. Consequently, certain assumptions were required in the economic assessment, which may affect the precision of the estimated costs and benefits. A further limitation of this study relates to the assessment of social benefits. Although the contribution of NBWS to the local economy may indirectly support social outcomes such as employment and community well-being, the lack of suitable data prevented the explicit quantification of broader social impacts, including water security, public health improvements, and stakeholder participation. Future studies should seek to incorporate dedicated social indicators to enable a more comprehensive sustainability assessment.

Finally, uncertainties associated with future economic conditions, water tariffs, and operational performance were only partially explored through sensitivity analysis.

Future research should focus on collecting long-term performance and cost data from a wider range of NBWS applications to improve the accuracy and reliability of economic assessments. Further studies should also apply the PSR-CBA framework across diverse case studies and regional settings to evaluate its broader applicability. In addition, integrating probabilistic uncertainty analysis, advanced scenario modelling, and more comprehensive valuation methods for ecosystem services could further enhance the robustness of the framework and support more informed decision-making regarding investments in nature-based water solutions.

7. Transferability and future applications

The proposed PSR-CBA framework is transferable to other regions and scales provided that adequate technical, environmental, and economic data are available. Its application, however, is influenced by local factors, including operating costs, climatic conditions, regulatory frameworks, and market characteristics. Policy support mechanisms, such as capital subsidies and tax incentives, may improve the economic attractiveness of Nature-Based Water Systems (NBWS), although they are not essential for the applicability of the framework. In the present case study, the economic viability of the system remained positive even in the absence of the capital subsidy, indicating that the framework can be employed under different policy scenarios. Future applications should consider region-specific conditions and stakeholder priorities to ensure robust and context-appropriate assessments.

CRediT authorship contribution statement

Mahdieh Ghafourian: Writing – original draft, Visualization, Validation, Resources, Methodology, Investigation, Formal analysis, Conceptualization, Writing – review & editing. **Georgios Archimidis Tsalidis:** Writing – review & editing. **Alireza Mousavi:** Writing – review & editing, Supervision. **Chrysanthi-Elisabeth Nika:** Writing – review & editing. **Eric Mino:** Writing – review & editing. **Evina Katsou:** Writing – review & editing, Supervision.

Declaration of competing interest

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.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.sftr.2026.102107.

Data availability

Data will be made available on request.

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