Science of the Total Environment 822 (2022) 153602

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Economic impact assessment indicators of circular economy in a decentralised circular water system — Case of eco-touristic facility

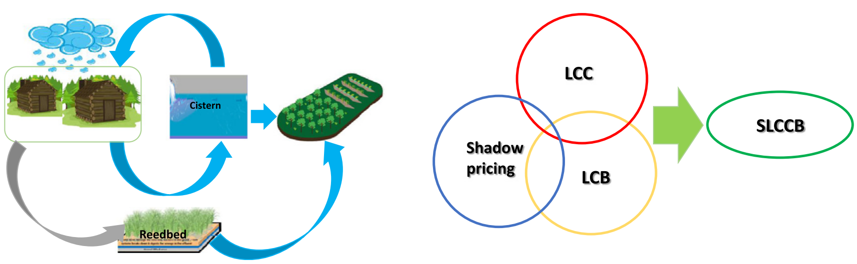
Mahdieh Ghafourian [a], Chrysanthi-Elisabeth Nika [a], Alireza Mousavi [b], Eric Mino [c], Maha Al-Salehi [c], Evina Katsou [a,*]

[a] Department of Civil & Environmental Engineering, Brunel University London, Uxbridge Campus, Middlesex UB8 3PH, Uxbridge, UK
[b] Department of Mechanical and Aerospace Engineering, Brunel University London, Uxbridge Campus, Middlesex UB8 3PH, Uxbridge, UK
[c] Technical Unit of the Euro-Mediterranean Information System on Know-how in the Water Sector, 06901 Sophia Antipolis, France

HIGHLIGHTS

- The economy of transition from linear to a circular model
- Suggesting a comprehensive economic assessment framework for circular water system (CWS)
- Monetizing the environmental and social gains of circular technologies in water industry
- Hybrid water systems are sensitive to Discount rate and reclaimed water tariff.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 20 September 2021
Received in revised form 27 January 2022
Accepted 28 January 2022
Available online 2 February 2022

Editor: Paola Verlicchi

Keywords:
Circular economy
Water systems
Economic assessment
Life cycle cost-benefit
Shadow pricing
Cost modelling

ABSTRACT

The transition from a linear make-use-dispose model to a Circular Economy (CE) model has gained momentum in recent years. To date, substantive efforts have been put by researchers and practitioners on environmental assessment of circular water systems (CWS). Yet, the economic aspect of CWS has not received the same attention. This research is an attempt to bridge this gap by evaluating the economic viability of a decentralised hybrid rainwater- wastewater-greywater (HRWG) system. For this purpose, a framework of Shadow Pricing- Life Cycle Cost-Benefit (SLCCB) to analyse a CWS is proposed. Shadow pricing could compliment the established Life Cycle Costing (LCC) methods. The main parameters (costs and benefits) of the proposed SLCCB framework are divided into two types: *Internal* and *External*. The Internal pricing covers the capital expenditure (CAPEX) and operational expenditure (OPEX), while the External pricing covers the environmental and social costs-benefits of implementing CWS. The proposed SLCCB added to the classical Net Present Value (NPV) and Payback Period (PP) calculations could provide a more realistic evaluation of the economic performance of CWS. To demonstrate the efficacy of the new CE model, a new CWS in Greece was studied.

A sensitivity analysis was conducted to assess the impact of the reclaimed water tariffs, internal costs, life span of the project, and the annual discount rate on the SLCCB. The results of the study reveal that the SLCCB of CWS is highly sensitive to these parameters. The economic feasibility of CWS boost with increasing discount rate and reclaimed water tariffs, as well as with decreasing project's life span and internal costs. The conclusion of this research demonstrates that investment in CWS is economically viable if *External* parameters are taken into consideration.

1. Introduction

Circular Economy (CE) is rapidly gaining the attention of governments, industrialists, and researchers. CE is about "closing material loops" and is providing the impetus for smarter use of natural resources, recycling and reusing materials and nutrients to gain full value at the minimum expense (MacArthur, 2016; Naustdalslid, 2014; Scheepens et al., 2016; Zink and Geyer, 2017; Dominguez et al., 2018). Despite the efforts by the European Union towards transitioning to CE, the true lack of understanding the true economic benefits-costs of products and CE enabling technologies act as a barrier to the transition from linear to CE (Ghafourian et al., 2021).

* Corresponding author.
E-mail address: evina.katsou@brunel.ac.uk (E. Katsou).

http://dx.doi.org/10.1016/j.scitotenv.2022.153602

The industrial scale transition towards CE without accurate cost recovery model that encompasse full cost and benefit of CE-based policies is difficult to justify (CCME, 2006).

Water appears a vital resource to be considered in the CE because of its critical importance with respect to human life, ecosystems functioning, industrial production, materials and energy it contains (Veolia UK Sustainability Report 2014). To ensure the achievement of global climate targets, the linear economic model of "end-of-pipe" pattern needs to be replaced with the CE model of "circular" pattern, by preserving resources in use and reviving rather than degrading them.

Capturing low-quality urban water sources as well as using non-conventional water resources present one possible solution to reduce the abstraction of freshwater resources which are becoming scarcer. Such non-conventional water resources include rainwater, greywater, stormwater, and wastewater to supply non-potable water uses, which are more than 20% of total water consumption in a building (Leong et al., 2018). Notably, in non-residential buildings, non-potable water uses are estimated of contributing more than 50% to the total water consumption (Campos Cardoso et al., 2020), including toilet flushing and urinals (Penn et al., 2013; Şahin and Manioğlu, 2019; De Silva and Hornberger, 2019), industrial processes, cleaning (Morales-Pinzón et al., 2014) and irrigation (Unami et al., 2015; Pacheco et al., 2017). Recovered water can also provide some beneficial resources proving additional added value. For example, in the case of treating wastewater by applying the CE concept, there would be several different valuable sources, such as the reclaimed water coming from treated wastewater, and the valuable resources such as nitrogen, phosphorous, and organic matter which are recovered and can be used as fertilizers (Abu-Ghunmi et al., 2016).

Unlike centralised systems, decentralised Greywater reuse (GWR), Wastewater recycling (WWR), and Rainwater harvesting (RWH) allow the treatment of rainwater and greywater at the source, which reduces the cost of transportation and collection of water. These costs could account for over 60% of the total budget of wastewater management, especially in communities with low population densities (Massoud et al., 2009). By alternating between rainwater, wastewater, and greywater, the combination of RWH, GWR, and WWR generates a unique hybrid decentralised rainwater-wastewater-greywater (HRWG) system that improves main water savings far from any of RWH, WWR, or GWR (Loux et al., 2012). According to Penn et al. (2013), Hybrid rain-grey water system (HRG) reduces the cost of treatment by reducing wastewater level to centralised wastewater treatment plants.

To reduce the impact of water scarcity and the demand of urban water supply that are caused by increasing population density and changing precipitation patterns, non-potable water in buildings can be appropriately substituted by rainwater or greywater (Campisano et al., 2017). Therefore, in some countries including Brazil, Germany and Australia, the installation of water reuse systems such as RWH, GWR, or HRG is encouraged or required in new buildings to capture and reuse non-potable water (Chen et al., 2021).

2. Economic method used to assess the performance of a decentralised water system

The economic impact of decentralised RWH, GWR, and HRG is a primary criterion for approving or disapproving a project (Chong et al., 2013). Previous research has concentrated on the life-cycle costs (LCC) of RWH and GWR systems at both the residential and commercial building scales, but few have examined HRG systems (Leong et al., 2019).

Inadequate system evaluation before implementation can cause an increase failure and maintenance costs (Abdallah et al., 2020). To support the adoption of water reuse systems, feasibility analysis of RWHs and GWRs in various areas and building types is required (Wang and Zimmerman, 2015; Silva et al., 2015; Stephan and Stephan, 2017; Wanjiru and Xia, 2017; Pradhan et al., 2019; Calliari et al., 2019). Ghisi and Mengotti de Oliveira (2007) analysed two residential structures in Brazil that had RWH and GWR installed. By installing the two systems separately, the potable water-saving efficiency could reach 35.5% and 33.6% for RWH and 30.4% and 25.6% for GWR, respectively, whereas by reusing rainwater and greywater together, the potable water-saving efficiency could reach to 36.4% and 33.8%, respectively. Both RWH's performance and economic benefits of RWH are influenced by the climate conditions in the investigated area (Tavakol-Davani et al., 2016). For example, according to Bashar et al. (2018), the capital and operation cost of implementing of RWH in rainy Bangladesh can be recovered within 2–6 years, whereas in a city in Pakistan that is located in cold semi-arid and warm desert environments, the benefit-cost ratio of RWH is less than 1.0 because the scant rainfall cannot meet the water demand (Ali et al., 2020). Greywater, as a non-potable water alternative, is more reliable than rainwater since it is not affected by weather patterns and can supply non-potable water demand, but its water quality is inferior to rainwater's (Leong et al., 2018). Mourad et al. (2011) analysed the economic feasibility of GWR in a residential building in Syria. They calculated the payback period of two different GWR system of artificial wetland (AW) and commercial biofilter (CBF), and the results showed the AW has a shorter payback period of 7 years in comparison to 52 years for a CBF system.

By developing ERain which is an economic analysis tool based on life cycle cost analysis, Amos et al. (2018) evaluated the financial effects of RWH in developed countries. They calculated the relationship and difference between the benefit-cost ratio, reliability, and the net present value (NPV) as economic indicators. The results showed that to increase economic feasibility of rainwater harvesting systems, a reduction in capital and operational and maintenance costs is preferred rather than raising the water price.

Roebuck et al. (2011) evaluated a total of 3840 domestic systems in the UK, considering the different stakeholder viewpoints and possible cost scenarios based on a mixture of 4 discount rates, 4 discount intervals, 3 water use combinations, and 5 occupancy rates, resulting in 240 simulation scenarios. They used 37 years of continuous daily rainfall records in their model and concluded that a domestic RWH in the UK had a low return on investment (ROI), with payback durations exceeding the RWH lifecycle, and that, notwithstanding the assumptions made at the time, domestic RWH systems in the UK were unlikely to deliver any reasonable payback term. The RWH system's financial loss is equivalent to its initial investment. It illustrates the significance of taking full account of all the related maintenance costs coupled with modern RWH systems. To assess the environmental impact of a hybrid greywater reuse- main water system (GWR-MWS), Jeong et al. (2018) by applying a life cycle assessment found that the environmental performance of the hybrid GWR-MWS is higher than centralised MWS in Atlanta, Georgia. To evaluate the economic and environmental impact (eco-efficiency) of two small-scale, decentralised wastewater treatment systems connected to constructed wetlands, Resende et al. (2019) performed Life cycle cost (LCC) and life cycle analysis (LCA). A vertical and horizontal flow wetland make up system 1 and a vertical subsurface flow wetland with artificial aeration is part of system 2. The results showed that when the cost of land and energy are taken into account, systems 2 is more feasible to be employed as it is cheapest alternative.

In order to widely deploy HRWG, it is required to investigate its operational properties in a variety of settings. Previous studies mostly have concentrated on the assessment of either RWH, and GWR at urban area, and only some have performed an analysis of hybrid systems (Leong et al., 2019). In addition, the analysis of hybrid systems has been limited to residential and commercial structures, with a focus on water conservation and environmental impacts.

Marinoski and Ghisi (2019) proposed a technique for evaluating the performance of an HRG in a single-family residential building in Brazil using a life cycle assessment (LCA). The HRG achieved a 41.9% water-saving proficiency, a 40% draining cutback rate, and a 36.1% energy utilization cutback rate, according to the findings. Based on the RainTANK model for the rainwater system and a simple continuous mass balancing model for the greywater system, Leong et al. (2018) estimated the water-saving performance of putative HRGs in a commercial and residential structure in Malaysia. According to these studies, the HRG in a commercial building should prioritize greywater and rainwater harvesting to fulfil the remaining water demand, whereas the HRG in a residential building should predominantly reuse rainwater.

To promote the application of HRWGs from Green buildings to urban areas, an environmental and economic evaluation of HRWG is required. To make a valuable economic analysis that can be a reference for stakeholders for decision making to adopt the CE model in the water industry, it is necessary to monetise and calculate the environmental and social costs and benefits (externalities) associated with CE as well as the economic cost and benefit (Ghafourian et al., 2021).

An externality is an economic concept that occurs when producing or consuming a good or service and causes an impact on third parties not directly linked to its creation (Molinos-Senante et al., 2014). An externality can either be positive or negative. Amos et al. (2016) argue different kinds of externalities resulted from water-reuse projects such as: (i) a reduction in freshwater diversion from complex ecosystems, (ii) a drop-in discharge to sensitive water bodies, (iii) creation and enhancement of wetlands using recycled water, and (iv) reduction and prevention of pollution. The problem for external impact to be included in economic analysis is that they do not have commonly approved monetary market value. Therefore, their quantitative value can be obtained through several economic estimation methods including travel cost, contingent valuation, hedonic property pricing, and shadow pricing. The hedonic pricing has a number of flaws, including the inability to capture merely consumers' willingness to pay for perceived environmental changes and their repercussions. The travel cost and the contingent valuation approach are not suitable for our estimation since the travel cost technique has a limited use and it cannot be used to assign values to on-site environmental elements and the bias introduced by individuals with interests other than assuring the accuracy of the results is a major flaw in the contingent valuation approach (Czembrowski et al., 2016). Hence, in the absence of accurate market prices, a monetary value of unknown or difficult-to-calculate costs can be estimated by shadow pricing method. It is based on the willingness to pay principle, which states that the most accurate assessment of a good's or service's worth is what people are willing to give up to obtain it. The shadow pricing is based on the distance function of Fare et al. (1993), and it has the benefits of being less costly in contrast with other methods like contingent estimation methods that involve surveying practices (Hernández-Sancho et al., 2010). Therefore, the shadow pricing has been selected in this study as an approach to estimate the monetary value of environmental externalities.

Reviewing the stated studies and more research in the literature show that to the best of the authors' knowledge, (i) former studies mostly have concentrated on the life cycle analysis of RWH or GWR individually and there is an information gap of how a circular model in water system included RWH, WWR and GWR together (HRWG) would perform, only a few studies have analysed the hybrid rainwater-greywater system (HRG) (Leong et al., 2019), (ii) also, the majority of these studies consider a decentralised water system in the domestic or industrial building and not in an eco-touristic facility. (iii) the number of studies that take into account the external benefit to estimate the economic impact of applying a CE is upstart or limited, so the impact of externalities remains unclear.

This study aims to evaluate the economic viability of a decentralised HRWG circular water system in an eco-tourist facility, for broadening the HRWG's application to a wider range of building types, which is crucial in the early phases of HRWG development. For this assessment, the implementation of a CWS in Tinos island, Greece was selected which is part of the European Union funded project HYDROUSA (grant agreement No 776643). Its data were used to establish a model of daily water balance for evaluating the potable water-saving operation, reduced electricity consumption, and economic benefits. The simplified plan of implementing the CWS of decentralised HRWG in Tinos Island is shown in Fig. 1.

The results contribute to the present knowledge of the implementation of the circular HRWG water system by (i) delivering detailed information on the life cycle analysis of a decentralised hybrid rainwater-greywater system applicable to the decision-making progression of local people on the island of Tinos and, (ii) developing an economic model to be used by decision-makers for other regions. Furthermore, a sensitivity analysis was performed to reveal the financial viability of decentralised HRWG systems based on the variation of the discount rate, lifespan, capital cost, and reclaimed water price.

3. Materials and methods

3.1. Study area

The proposed economic assessment framework is tested in an eco-touristic facility in Greece called Tinos Ecolodge. Tinos Ecolodge aims to

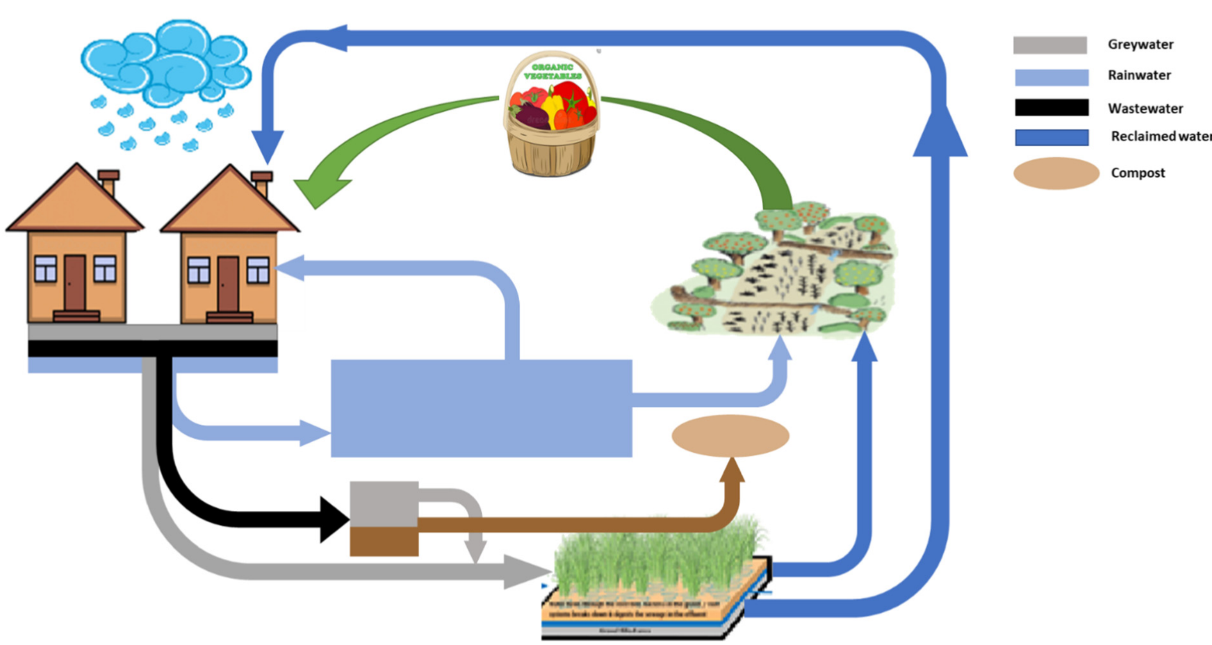


Fig. 1. CWS in the island of Tinos, Greece.

provide an eco-friendly tourist resort on the island of Tinos. The resort uses the island's natural resources in a sustainable manner, develops decentralised water and wastewater management loops and establishes an independent, state-of-the-art off-grid energy system. The eco-tourist facility is located on the island's east side, 14 km from Tinos port and 2.7 km from Steni, Tinos. Like the rest of the Cyclades Islands, Tinos has an average annual rainfall of 300 mm, making water a limited resource on the island. Fig. 2. shows the location of the Ecolodge in Tinos.

The Greek Island of Tinos is in the Eastern Mediterranean region located in the Aegean Sea. The area and population of Tinos are 195 km^2 and $\sim$ 9000 people, respectively. The island is a well-known tourist destination, with a total of four million visitors in 2017. The island's tourist industry and tourism-related sectors (e.g. accommodation, food services, retail commerce, and construction) are the main local economic activities representing more than 60% of employment and 65% of the island's total gross value added.

3.2. System specification

The water and wastewater loops in HYDRO6 include the rainwater harvesting, wastewater treatment by reedbed and UV disinfection, greywater reuse and irrigation of local crops with harvested rainwater and reclaimed wastewater. The state of the art on this CWS is the innovative and novel combination of water management cycles with agricultural and touristic activities. Within the eco-tourist facility non-conventional water sources are recovered from sewage, and rainwater, to cover the needs of the tourists using the facility. While some of the technologies are already in place, they will be expanded and updated in order to be a CWS to grow a wider variety of local crops, greenhouse and improve the facility's water conservation and recovery. The main key performance indicators to consider is: 50 m^3/year of rainwater harvested and 20–30 m^3/year of reclaimed water. The system can harvest and store enough rainwater to supply the needs for 16 people throughout the 4 dry summer months. In order to collect around 100,000 L of rainwater for irrigating the crops, a hard surface of 240 m^2 to harvest the rainwater is used. The rainwater harvesting systems were upgraded by constructing a new closed cistern, which will collect rainwater from the roof of an existing stable. Construction of new piping system from roof to the new closed cistern is required. A new wastewater treatment system will be built including a small sedimentation tank, and an upgraded reedbed system in order to use the treated water for agricultural irrigation to produce crops for tourist consumption. A reedbed filtration plant treats the residential sewage from 2 to 3 dwellings in the current sewage treatment unit. To disinfect the reedbed effluent, the wastewater treatment system was upgraded with a UV unit that allows reuse of the treated wastewater. The purified water will be utilized to irrigate various agricultural crops for local consumption and for local shops. The eco-touristic facility is located in a remote, off-grid location. Therefore, in the new system, photovoltaic (PV) panels were constructed to power the wastewater and water systems, using a renewable energy source, further addressing the closed loop approach. In addition, an 80 m^2 greenhouse was built in the new system (CWS) to increase productivity, climate control, energy and water savings for a variety of crops.

The closed water and wastewater loops provide a self-sufficient system with the following specifications: (i) no external water supply is required except for potable water use (ii) a 0.2 ha agricultural system (local crops and aromatic herbs) is irrigated with both rainwater collected from the roofs and reclaimed wastewater; (iii) onsite production of soil conditioner fertiliser; (iv) the produced food is consumed within the eco-touristic facility and part is sold to local shops and restaurants; (v) to increase awareness of the visitors on sustainable water practices.

3.3. Mains water system (MWS) vs. hybrid rain-waste-grey water system (HRWG)

The main water system (MWS) is the sole source of external *input* water in the Ecolodge coming from the treatment of freshwater and seawater to produce potable water that is distributed to the whole island. This potable water is also used for all non-potable uses including toilet flushing. The *output* water is all collected from *wastewater* and after collection is pumped to a centralised wastewater treatment facility.

In the CWS AQUATRON toilets are used to separate solid waste and liquid waste. The liquid waste is pumped to the settling tank where the greywater from sink and shower is collected. The water then pumps to reedbed and UV unit to be treated and disinfected in order to be reused. Toilet flushing and irrigation are considered as the end use of treated wastewater, greywater and harvested rainwater in the present study. Based on the data from monitored site, specific energy requirements for all activities was set to 828 kWh/year based on the measurement on site. Greek electricity prices are set in 0.1 €/kWh in the present calculation. A water flow diagram of the hybrid rain-waste-grey water System (HRWG) installed in the ecolodge can be seen in Fig. 3.

Fig. 4 presents the water requirement as a percentage for different water uses in a typical household. The data was obtained by ELSTAT (Fig. 4) It includes water for irrigation and toilet flushing as the main water usage at the ecolodge. The collected data shows a significant percentage of the total water demand for the two purposes.

Table 1 summarizes the specifications of the HRWG water system in the Ecolodge. Wastewater-Greywater is collected and diverted to a 0.5 m^3 storing tank then pumped to a VF reedbed, followed by a UV Unit to disinfect the water before its reuse. To compute the volume of reclaimed water produced, the total water demand for two residences with eight people each, inhabited 60% of the year, was multiplied by a fraction of washbasins, washing machines, and showers (63%) according to ELSTAT (2021). The result came as of 1066 m^3/year of wastewater- greywater collected and reused.

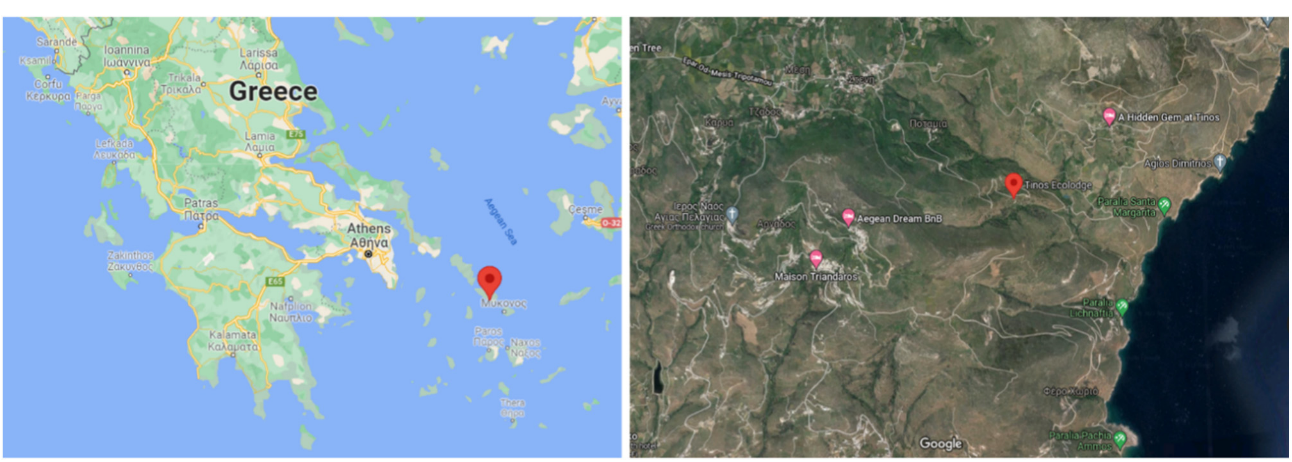


Fig. 2. Location of the studied area.

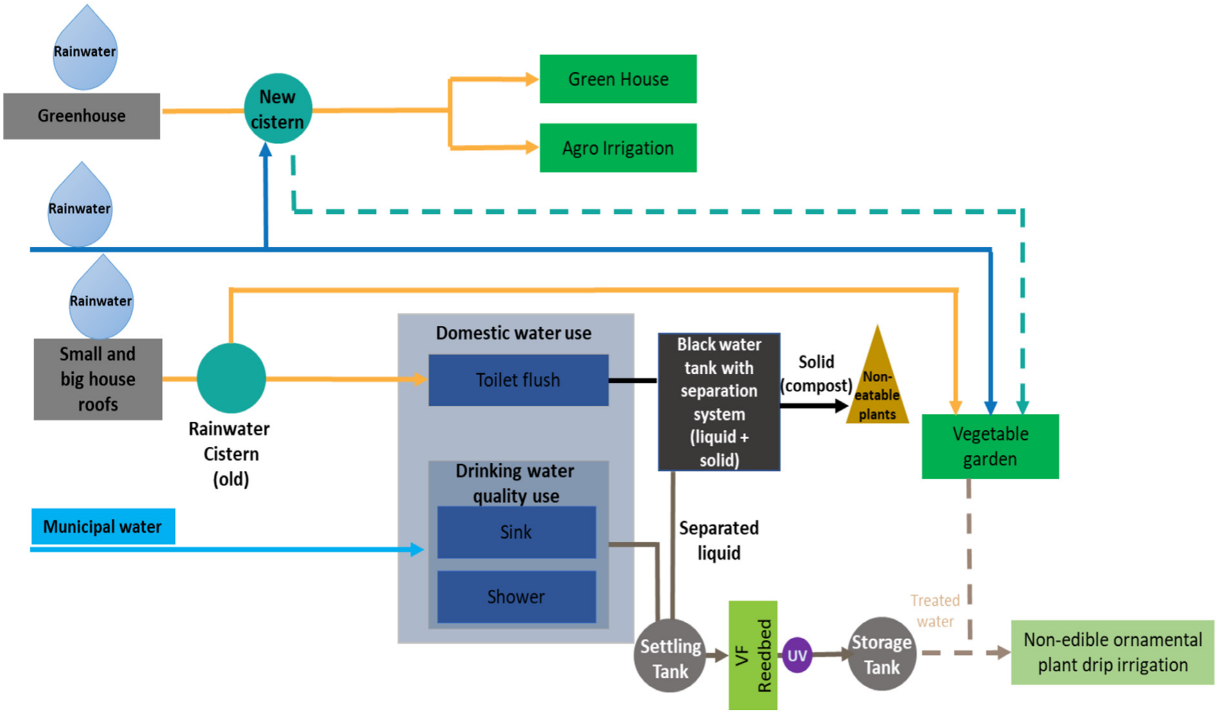


Fig. 3. Circular water system (CWS) of HRWG in Tinos Ecolodge.

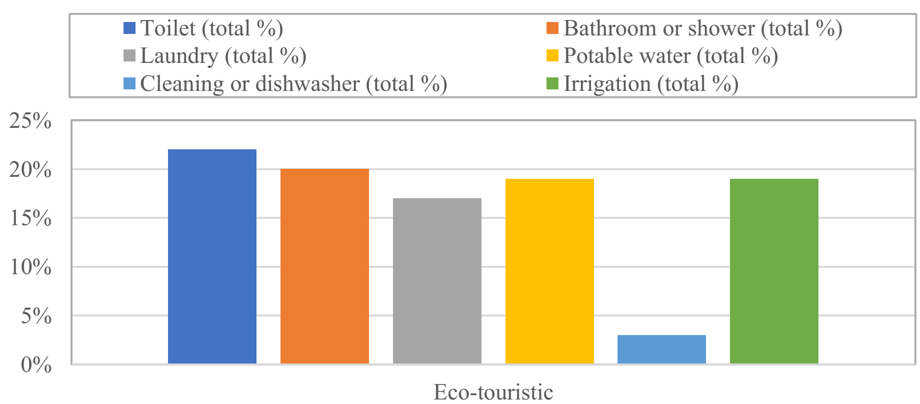


Fig. 4. Water consumption for different water uses in households (local data of Tinos Island obtained by ELSTAT).

Table 1
Specification of decentralised RWH and GWR in Tinos.

Rainwater harvesting inputs/outputs	
Total catchment area (roof top) (m^2)	400
Total rainwater tank volume (m^3)	165
Average rainfall (mm/year)	300
Irrigation (crop and greenhouse) water demand (m^3/year)	1066
Number of rainwater pumps	2
Rainwater met a certain percentage of non-potable demand (%)	59%
Greywater recycling inputs/outputs	
Quantity of greywater tanks	1
Volume of greywater tank (m^3)	3.8
Average monthly wastewater influent volume (m^3)	5
Volume of treated greywater allocation (m^3/year)	51
Number of greywater pumps	2
Greywater met a certain percentage of non-potable demand (%)	41%

3.4. System boundary

The system boundaries considered in this study for the HRWG are shown in Fig. 5, including the detailed processes of the system. In this study CAPEX, OPEX, economic revenues and external revenues (environmental and social) are considered for the CWS implemented in the Ecolodge. The piping infrastructure used to connect the MWS to the building's plumbing system and the internal main water pipes are not included in the calculation. Only the material and energy costs associated with additional pipelines that are used to upgrade the linear system to a circular HRWG system are included in this LCCB assessment.

The extraction, processing, and fabrication of raw materials, as well as the transportation of all components of HRWG systems, constitute the construction phase of the system. On-site transfer activities (e.g. transportation) and end-of-life phases (i.e recycling, landfilling and incineration) have been removed from this analysis because of their minimal

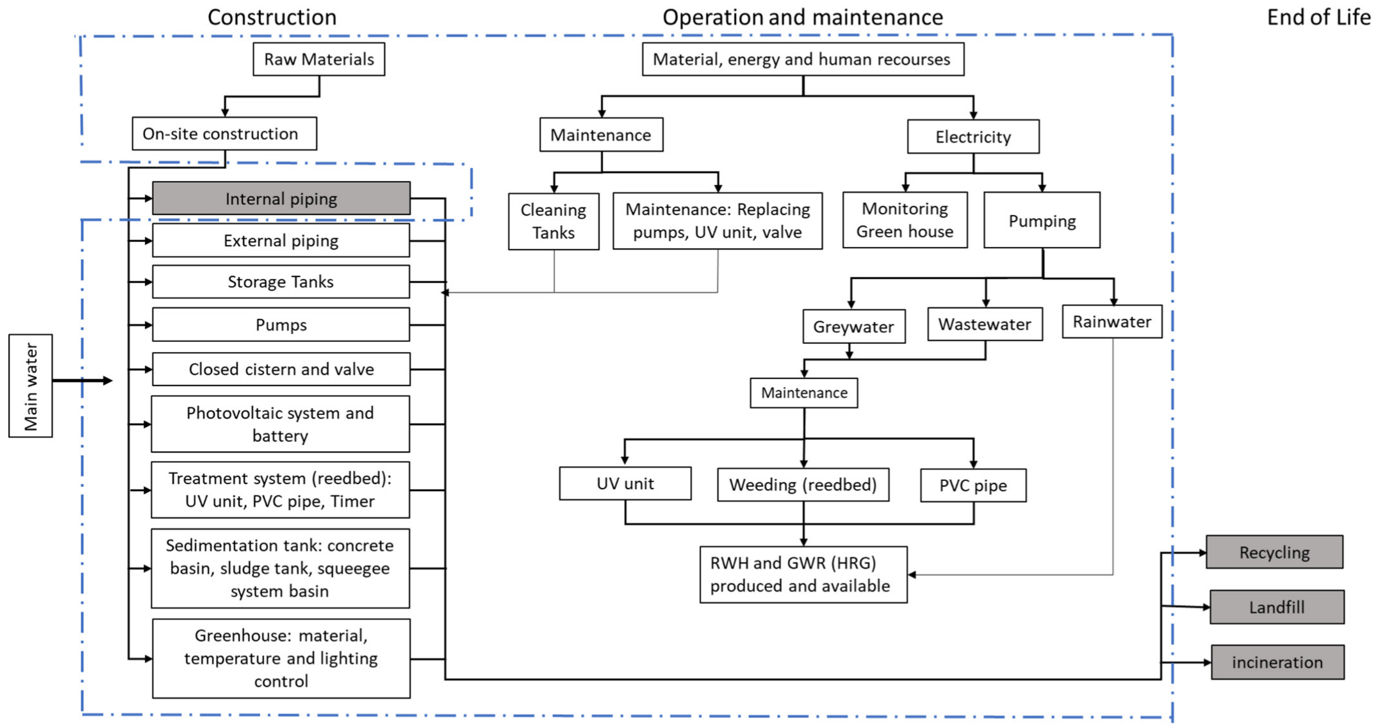


Fig. 5. System boundary for HRWG water system (grey section is excluded in our assessment).

implications similar to previous study (Hasik et al., 2017; Angrill et al., 2012; Scheuer et al., 2003; Junnila and Horvath, 2003).

In the operation phase, nine actions are included in LCC assessment as follows: (1) On-site electricity is used to pump rainwater, greywater, and mains water throughout the building during the operation; (2) Replacing sand and filter in greywater treatment system; (3) Annual greenhouse operation & maintenance cost; (4) Cleaning of the rainwater/greywater tanks; (5) Pump and valve replacement; (6) avoided fertiliser (7) renewing the organic certificate/insurance; (8) human resources for system's operation.

Furthermore, in the operation phase, the following benefits have been taken into consideration: (1) the saving of reduced mains water consumption when rainwater and/or greywater is in lieu of mains water; (2) avoided chemical usage for treatment; (3) benefit coming from production of organic products; (4) benefit from avoided fertiliser import; (5) environmental benefit from carbon sequestration; (6) avoided environmental damage from waste; (8) school visits and tourism; and (9) employment.

3.5. Data requirement for economic analysis

Table 2 lists the general added costs and benefits of the CWS with suitable economic indicators in its life cycle. In the added cost section, the economic cost of CAPEX and OPEX for the CWS system were considered. In the added benefit section three types of benefits including economic, environmental and social benefit were measured. Social benefits include employment, tourist and school visit's growth, while environmental benefits include the waste reduction, evading of extra nutrient loads in water bodies, and carbon sequestration, which is the result of an innovative farming to sequester (absorb) carbon dioxide out of the atmosphere on the agriculture plots of the site. Economic cost and three sets of benefit data (economic, environmental, and social) are collected in this study. Data related to the construction costs (CAPEX) of the system were gathered from the project's relevant partners using the inventory in Appendix B. The operational and maintenance (OPEX) data were collected from project's partners based on the estimation of annual costs and benefits measurement. Data from project partners were used to calculate the amount of new (i.e. extracted) versus recycled/reused materials and the amount of produced waste. On-site measurements are used to calculate the economic value of waste-based fertiliser production, as well as savings on freshwater withdrawal (replaced with treated gey and rain water), and the quantitative revenue coming from sale of organic products (vegetable, herb, fruit). In order to incorporate the environmental benefits into the proposed framework, two separate estimations are made: the first is to estimate the amount of carbon sequestration (Appendix A) and the efficiency of wastewater treatment (Appendix B), and the second incorporates the assignment of a monetary value to these estimations, which is explained in detail in sub section (4.1.1). Additionally, project partners provided additional data on the

Table 2
General life cycle added costs and benefits of the Circular system (economic indicators).

Added cost		Added benefit		Applied
Capital cost	Material cost	Economic	Freshwater withdrawal savings (replaced by treated grey and rain water)	✓
	Installation		Benefit from organic products, irrigation crops, herbs, etc.	✓
	Legal affairs (e.g. permits)		Fertiliser production out of waste	✓
	Purchase and installation costs of additional technologies	Environmental	Environment benefit from carbon sequestration	✓
Operational cost	Total energy usage (kWh/year)		Wastewater treatment	✓
	Other consumable & maintenance costs		Reduction of negative impacts of extracting mineral (water, soil)	
	Organic certificate		Biodiversity	
	Human resources		Reduction of excess nutrient loads in water bodies	
		Social	School visits	✓
			Tourism	✓
			Employment (maintaining/creation)	✓

positive impact of school visits, tourism, and employment on the island, based on the ticket price sold for school visits, tourism revenue, and the total hours worked by operators on site.

3.6. Life cycle cost-benefit- shadow pricing analysis

In order to create a comprehensive economic assessment of the CE in a water system, *Internal* and *External* economic, social and environmental parameters is proposed. The challenge lies in translating external impacts including environmental, social and health to a monetary value, which requires a custom economic valuation method to be applied. The estimation of the "true" total cost and benefit needs to be considered to capture the overall performance of the transition to a CWS. Therefore, in the proposed economic model, the shadow pricing method was employed to monetise the cost and benefit of environmental externalities to generate a holistic estimate of this transition.

A new and inclusive framework called Shadow pricing Life Cycle Cost-Benefit analysis (SLCCB) summarizes the results of life cycle cost-benefit and cost- benefit analysis (CBA) as the sub-methodologies. The cost-benefit analysis has been used as the main evaluation method that financial agents use to assess the economic impacts through the whole life cycle of the project (Belli et al., 2001). Furthermore, to confirm the result from SLCCB two indicators of the payback period (PP) and net present value (NPV) were estimated. A project with a positive NPV and a PP less than the project's lifespan is feasible to be implemented. The flowchart presented in Fig. 6 shows the integrated SLCCB framework.

According to Zhang et al. (2020), and Hoogmartens et al. (2014) the LCCB only includes real money flows in the life of the project and the cost-benefit analysis (CBA) considers a period (time frame) and functional unit of the project to evaluate it. Therefore, as it is shown in Fig. 6 the integration of CBA, life cycle costing (LCC), life cycle benefit (LCB), and shadow pricing (S) methods is proposed to have a comprehensive economic assessment. The parameters and indicators in this model belong to two categories: i) the base-indicators, which are applicable for the analysis of majority of cases including NPV and PP; and ii) the case-indicators, which are case specific indicators. The latter indicator dpecifies environmental and social parameters of this study, such as carbon sequestration and employment growth. The purpose of the SLCCB assessment is to evaluate the environmental and economic implications of a decentralised HRWG over the course of a 20-year project. Since there are multiple functions incorporated in the Ecolodge (e.g., agricultural products, organic fertiliser, produced water, tourism services, etc.) the system expansion method is applied to determine the functional unit (Cederberg and Stadig, 2003). Since every activity and production directly depend on non-potable water recovery, the collection, storage, and distribution of 1 m^3 of non-potable water for toilet flushing and irrigation is considered as the functional unit (FU) in this study.

3.7. Life cycle cost- benefit (LCCB)

Eq. (1) shows the SLCCB of CWS, excluding transportation and internal piping expenses. The currency was computed in Euro (€).

$$SLCCB_i = LCC_i - LCB_i \tag{1}$$

where LCC_i is the life cycle cost of the CWS or year t after installation and, LCB_i is the life cycle benefit of the CWS for year t after installation.

The detailed equation for calculation of SLCCB using the life cycle costing equation by (Stec and Kordana, 2015) is shown in Eq. (2):

$$SLCCB_i = CX_i + \sum_{t=1}^{T} \frac{OMC_{i,t}}{(1+r)^t} - \sum_{t=1}^{T} \frac{(B_I + B_E)_{i,t}}{(1+r)^t} \tag{2}$$

where $CX_i$is the initial capital cost (Euro); $OMC_{i,\ t}$ is the maintenance and operational costs (Euro) for t years after installing; T is the lifespan of the project, and r is the yearly discount rate (%);B_I is the internal benefit; B_E is the external benefit.

The internal/economic benefits listed in Table 2, include revenues coming from the market value of harvested or recycled water, agriculture products including organic products, vegetable and herbs, savings in energy of pumping drinking water, saving in chemical for water treatment, savings

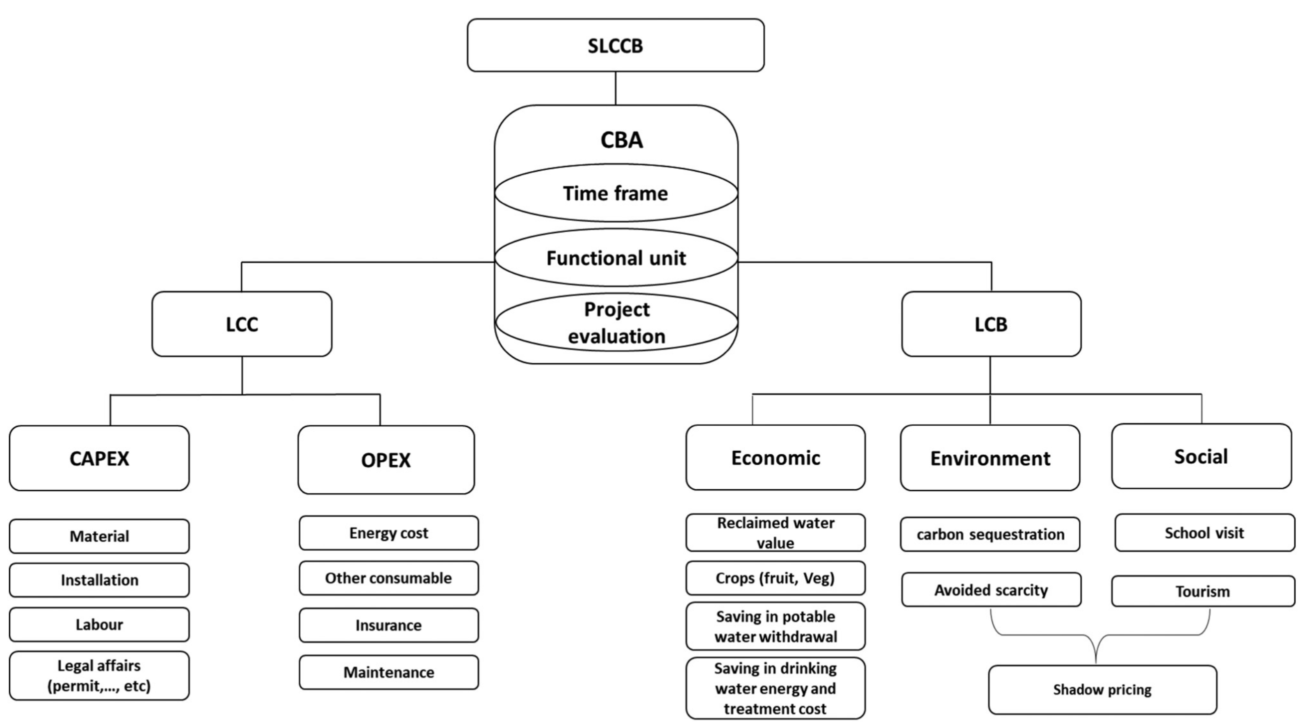


Fig. 6. Integration of LCC, CBA and shadow pricing methods.

in freshwater removal, and fertiliser production out of waste. Eq. (3) shows the internal benefit calculation:

$$B_I = \Sigma_{t=0}^{T}[(AVH_t * SPH_t) + (AVG_t * SPG_t) + (ACP_t * SPP_t) + (AVP_t * SPP_t) + (ACE_t * SPE_t) + (ACP_t * SPP_t) + (APF_t * SPF_t) \tag{3}$$

where B_I= internal benefit (€); AVH_t= annual harvested rainwater volume (m^3); SPH_t: market value of harvested rainwater (€/m^3); AVG_t= annual reclaimed greywater volume (m^3); SPG_t= market value of reclaimed greywater (€/m^3); AVP_t= annual agriculture products amount or weight (kg); SPP_t= market value of agriculture products (€/kg); ACE_t= annual cost of pumping (energy-saved) (kWh); SPE_t= market value of saved electricity (€/kWh); ACP_t= annual volume of saved potable water (m^3); SPP_t= market value of potable water (€/m^3).

3.7.1. Shadow price

According to Fare et al. (1993), the shadow price valuation of the undesirable outputs is established on the theory of directional distance function. In the present study the avoided costs linked with carbon sequestration (CS), reduction of waste, reduction of excess nutrient loads in water bodies, (i.e., environmental benefits) were estimated using the shadow pricing. It is determined by a combination of Hernández-Sancho et al. (2010) linear programming subject to constraints Fare et al. (1993) the distance function in Eq. (4):

$$\begin{aligned} \mathrm{LnD_0}(\mathrm{Input^p}, \mathrm{Output^p}) = \partial_0 &+ \Sigma_{i=1}^{I}\lambda_i * \ln\left(\mathrm{Input_i^p}\right) + \Sigma_{O=1}^{O}\nu_o \\ &* \ln\left(\mathrm{Output_o^p}\right)\Sigma_{i=1}^{I}\Sigma_{i'=1}^{I}\lambda_{ii'} * \ln\left(\mathrm{Input_i^p}\right) \\ &* \ln\left(\mathrm{Input_{i'}^p}\right) + \frac{1}{2}\Sigma_{o=1}^{O}\Sigma_{o'}^{O}\nu_{oo'} * \ln\left(\mathrm{Output_o^p}\right) \\ &* \ln\left(\mathrm{Output_{o'}^p}\right) + \frac{1}{2}\Sigma_{i=1}^{I}\Sigma_{o'}^{O}\omega_{io} * \ln\left(\mathrm{Input_i^p}\right) \\ &* \ln\left(\mathrm{Output_o^p}\right), \end{aligned} \tag{4}$$

where $\mathrm{Input^p}$ is the operational cost i (energy, staff, electricity, and other operation costs), $\mathrm{Output^p}$ is the external impact (environmental) of transition to CWS. According to Hernández-Sancho et al. (2010), the coefficients of the trans-log distance function (Eq. (4)) are explained by enhancing the objective function in Eq. (5) and using linear programming subject to system constrains:

$$Max \sum_{p=1}^{p} [(lnD_0(Input^p, Output^p) - ln(4)], \tag{5}$$

S(t).:

$$LnD_0(Input^p, Output^p) \le 0 \tag{5.1}$$

$$\frac{\Delta LnD_0(Input^p, Output^p)}{\Delta\, ln\,(Input_i^p)} \ge 0, p; \text{ Desired output} \tag{5.2}$$

$$\frac{\Delta LnD_0(Input^p, Output^p)}{\Delta\, ln\,(Input_o^p)} \le 0, p; \text{ Undesired output} \tag{5.3}$$

$$\sum_{o=1}^{O}\nu_O = 1, \sum_{o'=1}^{O}\nu_{OO'} = \sum_{o=1}^{O}\omega_{io} = 0 \tag{5.4}$$

$$\nu_{oo'} = \nu_{o'o}, \lambda_{ii'} = \lambda_{i'i} \tag{5.5}$$

For instance, in this study, the quantitative value of environmental impact of carbon sequestration, reduction of waste, and reduction of excess nutrient loads in water bodies, were calculated by Eq. (6) as developed by Molinos-Senante et al. (2011).

$$PE = \sum_{j=1}^{J} q_j VP_j \tag{6}$$

where PE = positive externalities (€/year) q_j = shadow price of the external impact j (€/kg) and VP_j= The amount of external impact j (kg/year).

3.8. Economic indicators

The PP and NPV are estimated SLCCB. The project with a positive NPV and the PP to be less than project life span (Boardman, 2015). NPV can be calculated by Eq. (7), and PP can be calculated by Eq. (8). If the NPV is negative, or the PP was not presented in the life span of a project, so the project is not economically viable.

$$NPV = \Sigma_{t=0}^{20}\left[\frac{(B_t - C_t)}{(1+i)^t}\right] \tag{7}$$

where B_t is the benefit; C_t= cost for t; t = years, i = discount rate. The analysis period is 20 years in this study, according to the European Commission, the discount rate for investment evaluation in Greece is 8% which is used in this study.

$$PP = \frac{CAPEX}{yearly\ revenues - OPEX} \tag{8}$$

3.9. Sensitivity analysis

To test the robustness of influential factors, including the price of reclaimed water (€/m^3), operation and investment cost (€/year), discount rate (%), and project's lifespan with a ± 25% variation, sensitivity analysis using graphical methods. The analysis covers a range of conditions that can arise during the implementation of the project subject to uncertainties. The parameters' robustness can be determined once the sensitivity of SLCCB to these parameters have been examined.

4. Results and discussion

In order to demonstrate the performance of the proposed economical assessment of CWS, live data from ongoing the site were used. The site is equipped with state-of-the-art industrial control and monitoring system, thus the quality of data acquisition is very good and reliable. The capital, installation, and annual operation and maintenance costs for the HRWG are summarised in Table 3. The Greek discount rate (location of the demonstrator sites) of 8% and a life span of 20 years is considered. Table 3 lists data gathered from partners and information from local norms of HYDROUSA (n.d.) demonstrator sites. The data for CAPEX, OPEX, and revenue were expressed per functional unit (FU) (i.e. collection, storage, and distribution of 1 m^3 of non-potable water for toilet flushing and irrigation).

Table 4. lists all the external factors used in the calculation of SLCCB.

4.1. Life cycle cost-benefits

The three *Internal* benefits that were considered in this study (Table 3), have different impacts on the local economy including, employment growth, almost full sufficiency of food production and reduction of unsustainable water demand through providing non-conventional water resources. In LCCB calculation the reclaimed water price was set to € 0.9 per m^3 according to Molinos-Senante et al. (2011) and the cost of drinking water (tariff for Greece) is €0.6 per m^3 according to Kanakoudis et al. (2016).

The system is economically viable if the Eq. (9) applies to the valuation.

$$LCB_{HRWG} - LCC_{HRWG} > 0 \tag{9}$$

The present value factor (PVF) and discount salvage factor (PFF) were considered in the calculation of LCC and LCB. In this instance, only internal cost and benefit were taken into consideration and based on Eqs. (2) and (3) following result is gained.

$$LCC_{HRWG} = 2744.95$$

$$LCB_{HRWG}(internal\ benefit) = 1382.1$$

Table 3
Circular water systems (CWS) cash flow.

Specification	Cost/Benefit	Unit	HRWG
CAPEX	Rainwater harvesting	€	524
	Reedbed and UV unit to disinfect	€	228
	Greenhouse	€	251
	Irrigation System	€	1.55
	Crop Processing	€	1.3
	Legal affairs	€	21
	Certifications	€	31.1
	Total	€	1057.95
OPEX	Value of annual electricity consumption (for pumping, treating,)	€	1.5
	Annual operation & maintenance cost for greenhouse	€/year	3.7
	Cleaning of the rainwater/greywater tanks (every 10 years)	€/year	1.23
	Mains top-up switch and valve replacement (every 5 years)	€/year	3.06
	Replacing sand in a filter of sand (every 5 years)	€/year	2.2
	Replace pump (every 5 years)	€/year	2.7
	Protentional Fertiliser	€/year	28.50
	Renewing the organic certificate/Insurance	€/year	16.75
	Human resources for system operation	€/year	136.64
	Total	€/year	195.568
	Freshwater withdrawal savings (replaced by treated gey and rain water)	€/year	6.99
	Benefit from organic products, irrigation crops, herbs from both greenhouse and in crops) (saving in importing products)	€/year	105.3
	Fertiliser production out of waste (saving in importing fertiliser)	€/year	28.50
	Total (Total saving)	€/year	140.79
CONDITION	Salvage value (Equipment value final year)	€	600
	Net discount rate (percent)	%	0.08
	Years of operation for the equipment	year	20

Based on Eq. (9) the CWS system would not be economically viable to be implemented in Tinos (one of the demo sites), when the external impacts are not taken into consideration.

4.1.1. Externalities and shadow prices

The shadow price method was applied to monetise the environmental benefits obtained from CWSs. The shadow price can be calculated using the estimation of the directional distance function for environmental impacts of reduction of waste (pollutants were removed during wastewater treatment). The shadow price of the waste reduction is the cost that would have been saved if pollutants were removed during wastewater treatment to avoid the environmental damage. In this study the shadow price of the five indicators including nitrogen (N), phosphorus (P), suspended particles (TSS), biological oxygen demand (BOD), and chemical oxygen demand (COD), that have been calculated by Hernández-Sancho et al. (2010) were considered. Indeed, the elimination of undesirable elements would be the equivalent of the avoided environmental damage or environmental benefits. The estimated value of these components, which is collected from relevant partners is presented in Tables 6 and 7 of Appendix B.

Table 4
External effects (environmental and social) considered in the calculation.

External benefit (social and environmental)	
Benefit	**Unit**
Carbon sequestration (CS)	Kg/year
Avoided environmental damage from waste	Mg/l
Schools visits	group of 5 students
Job maintenance	FTE (full time equivalent)
Tourist	Person/year
Yearly external revenues	

Table 5
Environmental and Social benefits of CWS.

Specification	Cost/Benefit	Unit	HRWG
External revenues	Environment benefit from carbon sequestration	€/year	5.49
	Avoided environmental damage from waste	€/year	6.8
	School visit	€/year	8.1
	Tourism	€/year	120
	Employment	€/year	19.7
	Total (Total saving)	€/year	164.39

The carbon sequestration from soil is estimated as 0.11 (t/year) per functional unit in line with Ex-ACT method from FAO - Cost of carbon (Fao, 2016). The FAO's EX-ACT (Ex-ante Carbon Balance Tool) provides an ex-ante estimate of the effects of land use and land use change on GHG emissions and carbon sequestration. EX-ACT depicts the impact of agricultural and forestry activities by utilising the carbon footprint as a measure of climate change mitigation. EX-ACT is used to estimate the amount of carbon that could be sequestered by various nature-based and inspired solutions (Table 5 of Appendix B). EX-ACT Tool estimates the monetary quantification for unit price in 41.5 to 81 €/t, which is the target value for the Paris agreement, based on a World Bank report on State and Trends of Carbon Pricing, 2020 (World Bank, 2019). In this study, 51 €/t was considered, which corresponds to the average of this agreed price range. The detailed calculation method is presented in Appendix A.

The social impacts of school visit growth, tourism growth, and employment growth were formed since the Ecolodge is upgraded to a unique agro-eco-touristic facility that is planned to attract organised visits from schools, as well as local and international tourists. To monetarised these impacts a more complex pricing method was used. The pricing method is the calculation of the value added to local economy in effect of a social effect. If the money coming from tourism and school visit is being spent on schools, cultural improvements, temple maintenance, and improve the image of the community, this income calculating as a social benefit (Morgan et al., 2015). On the other hand, the growth in tourism industry and agriculture prosperous increase the employment which influence the GDP and more specifically the local economy (CORE – Aggregating the world's open access research papers, n.d.). The quantitative value of the external impacts is demonstrated in Table 5.

Therefore, the Life cycle benefit of environmental benefit over a lifespan of 20 years and a discount rate of 8% is estimated to be:

$$LCB_{HRG}(External\ benefit) = 1614.9$$

By incorporating the external benefit,

$$LCB_{HRG}(internal\ benefit) + LCB_{HRG}(external\ benefit) - LCC_{HRG} > 0$$

$$252.05 > 0$$

The results show that by taking into consideration the environmental and social benefits a new perspective can emerge that could help decision-makers to select the most appropriate course, as well as to provide justification for CWS transition strategies.

4.2. Economic analysis using two indicators

Based on the acquired information from the sites, the NPV and PP of HRWG were calculated using Eqs. (7) and (8) results are shown in Table 6.

Table 6
The NPV and PP of the CWS.

Economic indicators	HRWG
NPV (€)	56.32
PP (year)	10.17

As indicated in Table 6, the circular HRWG water system is economically feasible to undertake as its NPV is more than 1 and the payback period is 10 years, which is less than projects lifespan of 20 years.

4.3. Sensitivity analysis

A sensitivity analysis was performed to test the sensitivity of SLCCB to reclaimed water tariff (€/m^3), discount rate (%), internal cost including CAPEX and OPEX (€/year), and life span of project (years). The results of the sensitivity analysis carried out with a ± 25% variation in discount rate. A corresponding shift in the performance of the SLCCB result is presented in Fig. 7 (a) as SLCCB increases with increasing discount rate. Fig. 7 (b) shows the result of the sensitivity analysis performed with a ± 25% variation in the capital cost (CAPEX). The corresponding shift in the performance of the SLCCB indicates that an increase in CAPEX, decreases the SLCCB linearly and a CAPEX more than 1089.29 is not economically viable if the other factors remain constant. Fig. 7 (c) demonstrates that increasing the mains water tariff linearly increases the financial viability of the HRWG water system. The HRWG becomes economically viable (NPV = SLCCB >0) at a water tariff of approximately 0.67 €/m^3. Fig. 7 (d) and (e) show that with an increase to life span or OPEX (the ±25% difference), system's viability decreases linearly. If the OPEX increases to 210 €/year, the circular system is not viable to carry out.

5. Conclusions

The transition from a linear make-use-dispose model to a CE requires a clear and inclusive economic justification, in order to project of the rate of return on investment. Although the environmental merits of CE are well articulated in existing literature, making a strong economic case for such a fundamental commitment requires real and accurate economic modelling.

This study provides an inclusive method to evaluate the economic feasibility of transforming linear water system to a circular. An eco-touristic facility in Tinos, Greece at a discount rate of 8% across 20 years was used as a case study. *Internal* and *External* economic, environmental and social costs and benefits are calculated and integrated within a Shadow pricing Life cycle cost-benefit (SLCCB). It could be considered as a comprehensive economic framework to compliment the classical PP and NPV calculations for investment of circular water systems.

The economic feasibility study was initially implemented in the target case study without considering the economic impacts of the environmental and social benefits. The results showed that the target system is not

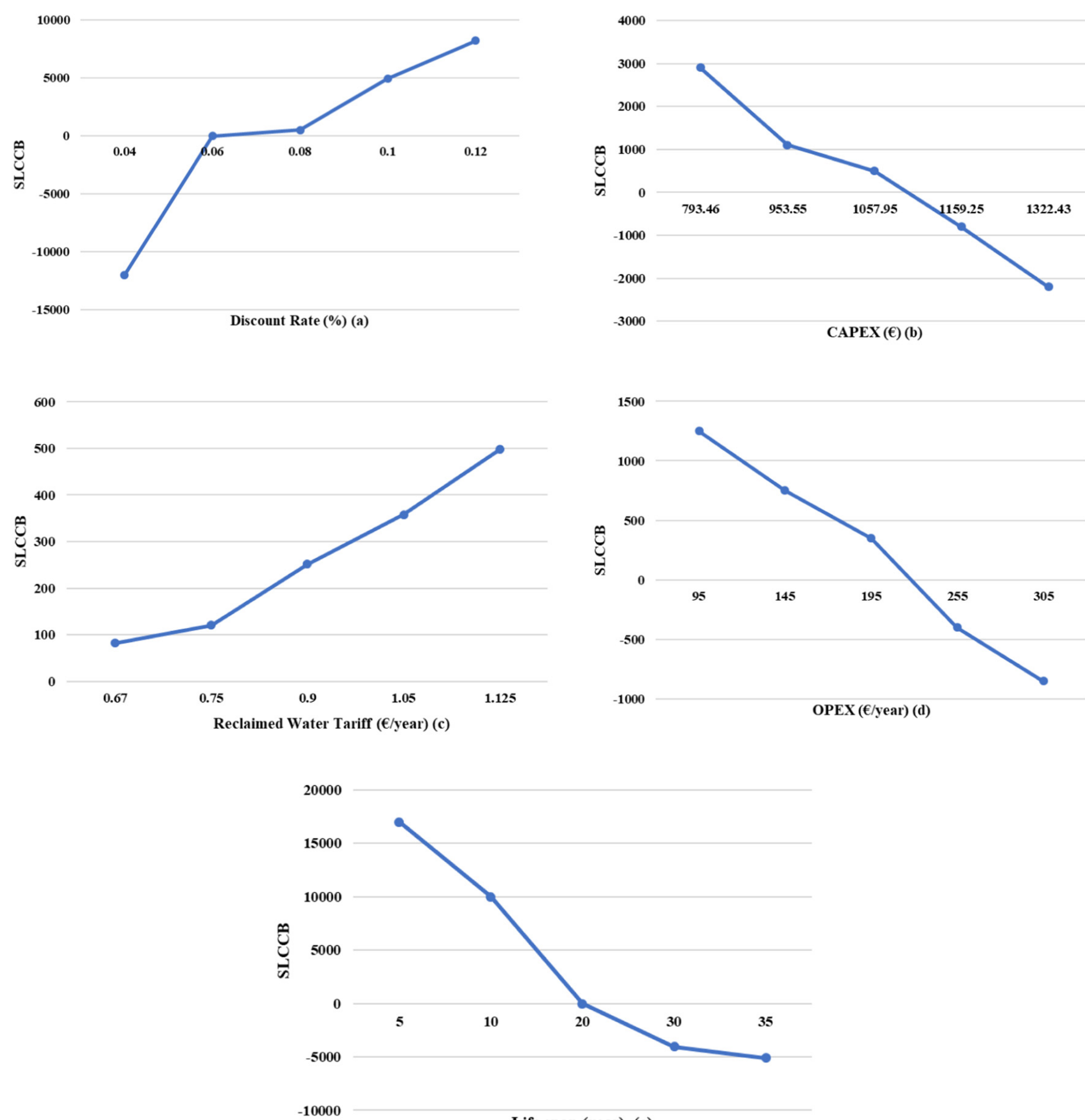


Fig. 7. Sensitivity analysis for SLCCB with respect to discount rate (a), capital cost (b), reclaimed water tariff (c), operation cost (d), and life span (e).

economically feasible. However, when the environmental and social benefits were added into the assessment frame, the results revealed that the system's PP would be around 10 years, and the NPV of the project is more than 1, confirming that implementing the CWS would be economically feasible, and returns investment in reasonable time. A sensitivity analysis revealed that the financial viability of CWS is significantly correlated with discount rates, the reclaimed water tariffs, OPEX, and CAPEX as control parameters of decision support.

The economic assessment methodology developed in this study demonstrates a robust and more realistic evaluation of CWS's economic performance and could be a realistic method of economic cost-benefit analysis for CWS initiatives, subjected the constraint of the locale.

CRediT authorship contribution statement

Mahdieh Ghafourian: Conceptualization, Methodology, Writing – original draft. **Chrysanthi-Elisabeth Nika:** Investigation, Writing – review & editing. **Alireza Mousavi:** Data curation, Writing – original draft. **Eric Mino:** Validation, Investigation. **Maha Al-Salehi:** Validation. **Evina Katsou:** Supervision, Writing – review & editing, Funding acquisition.

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.

Acknowledgement

This research was supported by the Engineering and Physical Sciences Research Council (EPSRC) [Grant agreement No EP/R512990/1] and the Horizon 2020 research and innovation program HYDROUSA (Grant agreement No 776643).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2022.153602.

References

Abdallah, M., Shanableh, A., Elshazly, D., Feroz, S., 2020. Techno-economic and environmental assessment of wastewater management systems: life cycle approach. Environ. Impact Assess. Rev. 82, 106378. https://doi.org/10.1016/J.EIAR.2020.106378.

Abu-Ghunmi, D., Abu-Ghunmi, L., Kayal, B., Bino, A., 2016. Circular economy and the opportunity cost of not "closing the loop" of water industry: the case of Jordan. J. Clean. Prod. 131, 228–236. https://doi.org/10.1016/j.jclepro.2016.05.043.

Ali, S., Zhang, S., Yue, T., 2020. Environmental and economic assessment of rainwater harvesting systems under five climatic conditions of Pakistan. J. Clean. Prod. 259, 120829. https://doi.org/10.1016/j.jclepro.2020.120829.

Amos, C.C., Rahman, A., Gathenya, J.M., 2016. Economic analysis and feasibility of rainwater harvesting systems in urban and peri-urban environments: a review of the global situation with a special focus on Australia and Kenya. Water (Switzerland) https://doi.org/10.3390/w8040149.

Amos, C.C., Rahman, A., Gathenya, J.M., 2018. Economic analysis of rainwater harvesting systems comparing developing and developed countries: a case study of Australia and Kenya. J. Clean. Prod. 172, 196–207. https://doi.org/10.1016/j.jclepro.2017.10.114.

Angrill, S., Farreny, R., Gasol, C.M., Gabarrell, X., Viñolas, B., Josa, A., Rieradevall, J., 2012. Environmental analysis of rainwater harvesting infrastructures in diffuse and compact urban models of Mediterranean climate. Int. J. Life Cycle Assess. 17, 25–42. https://doi.org/10.1007/s11367-011-0330-.

Bashar, M.Z.I., Karim, M.R., Imteaz, M.A., 2018. Reliability and economic analysis of urban rainwater harvesting: a comparative study within six major cities of Bangladesh. Resour. Conserv. Recycl. 133, 146–154. https://doi.org/10.1016/j.resconrec.2018.01.025.

Belli, P., Anderson, J.R., Barnum, H.N., Dixon, J.A., Tan, J.-P., 2001. Economic Analysis of Investment Operations—Analytical Tools and Practical Applications. World Bank, Washington D.C. 978-0-82134850-5.

Boardman, A.E., 2015. Cost-benefit analysis. International Encyclopedia of the Social & Behavioral Sciences, Second edition Elsevier Inc., pp. 47–54 https://doi.org/10.1016/B978-0-08-097086-8.71068-3.

Calliari, E., Staccione, A., Mysiak, J., 2019. An assessment framework for climate-proof nature-based solutions. Science of the Total Environment 656, 691–700. https://doi.org/10.1016/j.scitotenv.2018.11.341 Elsevier B.V.

Campisano, A., Butler, D., Ward, S., Burns, M.J., Friedler, E., DeBusk, K., Fisher-Jeffes, L.N., Ghisi, E., Rahman, A., Furumai, H., Han, M., 2017. Urban rainwater harvesting systems: research, implementation and future perspectives. Water Res. https://doi.org/10.1016/j.watres.2017.02.056.

Campos Cardoso, R.N., Cavalcante Blanco, C.J., Duarte, J.M., 2020. Technical and financial feasibility of rainwater harvesting systems in public buildings in Amazon, Brazil. J. Clean. Prod. 260, 121054. https://doi.org/10.1016/J.JCLEPRO.2020.121054.

CCME, 2006. WWW Document. https://www.ccme.ca/ (accessed 11.26.20).

Cederberg, C., Stadig, M., 2003. Milk and Beef Production LCA Case Studies System Expansion and Allocation in Life Cycle Assessment of Milk and Beef Production. https://doi.org/10.1065/lca2003.07.126.

Chen, W., Gao, W., Jiang, J., Wei, X., Wang, R., 2021. Feasibility analysis of decentralized hybrid rainwater-graywater systems in a public building in Japan. Sustain. Cities Soc. 69, 102870. https://doi.org/10.1016/j.scs.2021.102870.

Chong, M.N., Ho, A.N.M., Gardner, T., Sharma, A.K., Hood, B., 2013. Assessing decentralised wastewater treatment technologies: correlating technology selection to system robustness, energy consumption and GHG emission. J. Water Clim. Chang. 4, 338–347. https://doi.org/10.2166/wcc.2013.077.

CORE, n.d.CORE – Aggregating the world's open access research papers [WWW Document], n.d. URL https://core.ac.uk/ (accessed 7.15.21).

Czembrowski, P., Kronenberg, J., Czepkiewicz, M., 2016. Integrating non-monetary and monetary valuation methods – SoftGIS and hedonic pricing. Ecol. Econ. 130, 166–175. https://doi.org/10.1016/J.ECOLECON.2016.07.004.

De Silva, M., Hornberger, G.M., 2019. Assessing water management alternatives in a multi-purpose reservoir cascade system in Sri Lanka. J. Hydrol. Reg. Stud. 25, 100624. https://doi.org/10.1016/J.EJRH.2019.100624.

Dominguez, S., Laso, J., Margallo, M., Aldaco, R., Rivero, M.J., Irabien, Á., Ortiz, I., 2018. LCA of greywater management within a water circular economy restorative thinking framework. Sci. Total Environ. 621, 1047–1056. https://doi.org/10.1016/J.SCITOTENV.2017.10.122.

Fao, 2016. EX-ANTE Carbon-Balance Tool (EX-ACT) EX-ANTE CARBON-BALANCE TOOL (EX-ACT) Technical Guidelines EASYPol MODULE. 101.

Fare, R., Grosskopf, S., Lovell, C.A.K., Yaisawarng, S., 1993. Derivation of shadow prices for undesirable outputs: a distance function approach. Rev. Econ. Stat. 75, 374. https://doi.org/10.2307/2109448.

Ghafourian, M., Stanchev, P., Mousavi, A., Katsou, E., 2021. Economic assessment of nature-based solutions as enablers of circularity in water systems. Sci. Total Environ. 148267. https://doi.org/10.1016/j.scitotenv.2021.148267.

Ghisi, E., Mengotti de Oliveira, S., 2007. Potential for potable water savings by combining the use of rainwater and greywater in houses in southern Brazil. Build. Environ. 42, 1731–1742. https://doi.org/10.1016/j.buildenv.2006.02.001.

Hasik, V., Anderson, N.E., Collinge, W.O., Thiel, C.L., Khanna, V., Wirick, J., Piacentini, R., Landis, A.E., Bilec, M.M., 2017. Evaluating the life cycle environmental benefits and trade-offs of water reuse systems for net-zero buildings. Environ. Sci. Technol. 51, 1110–1119. https://doi.org/10.1021/acs.est.6b03879.

Hernández-Sancho, F., Molinos-Senante, M., Sala-Garrido, R., 2010. Economic valuation of environmental benefits from wastewater treatment processes: an empirical approach for Spain. Sci. Total Environ. 408, 953–957. https://doi.org/10.1016/j.scitotenv.2009.10.028.

Hoogmartens, R., Van Passel, S., Van Acker, K., Dubois, M., 2014. Bridging the gap between LCA, LCC and CBA as sustainability assessment tools. Environ. Impact Assess. Rev. https://doi.org/10.1016/j.eiar.2014.05.001.

Hydrousa, n.d.Hydrousa [WWW Document], n.d. URL https://www.hydrousa.org/ (accessed 8.21.20).

Jeong, H., Broesicke, O.A., Drew, B., Crittenden, J.C., 2018. Life cycle assessment of small-scale greywater reclamation systems combined with conventional centralized water systems for the City of Atlanta, Georgia. J. Clean. Prod. 174, 333–342. https://doi.org/10.1016/j.jclepro.2017.10.193.

Junnila, S., Horvath, A., 2003. Life-cycle environmental effects of an office building. J. Infrastruct. Syst. 9, 157–166. https://doi.org/10.1061/(ASCE)1076-0342(2003)9:4(157).

Kanakoudis, V., Tsitsifli, S., Gonelas, K., Papadopoulou, A., Kouziakis, C., Lappos, S., 2016. Determining a socially fair drinking water pricing policy: the case of Kozani, Greece. Procedia Eng. C, 486–493 https://doi.org/10.1016/J.PROENG.2016.11.092.

Leong, J.Y.C., Oh, K.S., Poh, P.E., Chong, M.N., 2018. Prospects of hybrid rainwater-greywater decentralised system for water recycling and reuse: a review. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2016.10.167.

Leong, J.Y.C., Balan, P., Chong, M.N., Poh, P.E., 2019. Life-cycle assessment and life-cycle cost analysis of decentralised rainwater harvesting, greywater recycling and hybrid rainwater-greywater systems. J. Clean. Prod. 229, 1211–1224. https://doi.org/10.1016/j.jclepro.2019.05.046.

Loux, J., Winer-Skonovd, R., Gellerman, E., 2012. Evaluation of combined rainwater and greywater systems for multiple development types in Mediterranean climates. J. Water Sustain. 1, 55–77. https://doi.org/10.11912/jws.2.1.55-77.

MacArthur, E., 2015. Foundation and Granta Design, 2015 Ellen MacArthur Foundation, Granta Design Circularity Indicators: An Approach to Measuring Circularity. Ellen MacArthur Foundation, London, UK.

Marinoski, A.K., Ghisi, E., 2019. Environmental performance of hybrid rainwater-greywater systems in residential buildings. Resour. Conserv. Recycl. 144, 100–114. https://doi.org/10.1016/j.resconrec.2019.01.035.

Massoud, M.A., Tarhini, A., Nasr, J.A., 2009. Decentralized approaches to wastewater treatment and management: applicability in developing countries. J. Environ. Manag. 90, 652–659. https://doi.org/10.1016/j.jenvman.2008.07.001.

Molinos-Senante, M., Hernández-Sancho, F., Sala-Garrido, R., 2011. Cost-benefit analysis of water-reuse projects for environmental purposes: a case study for spanish wastewater treatment plants. J. Environ. Manag. 92, 3091–3097. https://doi.org/10.1016/j.jenvman.2011.07.023.

Molinos-Senante, M., Gómez, T., Garrido-Baserba, M., Caballero, R., Sala-Garrido, R., 2014. Assessing the sustainability of small wastewater treatment systems: a composite indicator approach. Sci. Total Environ. 497–498, 607–617. https://doi.org/10.1016/j.scitotenv.2014.08.026.

Morales-Pinzón, T., Lurueña, R., Gabarrell, X., Gasol, C.M., Rieradevall, J., 2014. Financial and environmental modelling of water hardness - implications for utilising harvested rainwater in washing machines. Sci. Total Environ. 470–471, 1257–1271. https://doi.org/10.1016/j.scitotenv.2013.10.101.

Morgan, Westcott, Wendy, Anderson, Geoffrey, Bird, Peter, Briscoe, 2015. Introduction to Tourism and Hospitality in BC. 2nd edition. Simple Book Publishing (accessed 11.17.21). https://opentextbc.ca/introtourism2e.

Mourad, K.A., Berndtsson, J.C., Berndtsson, R., 2011. Potential fresh water saving using greywater in toilet flushing in Syria. J. Environ. Manage. 92, 2447–2453. https://doi.org/10.1016/j.jenvman.2011.05.004.

Naustdalslid, J., 2014. Circular economy in China - the environmental dimension of the harmonious society. Int. J. Sustain. Dev. World Ecol. 21, 303–313. https://doi.org/10.1080/13504509.2014.914599.

Pacheco, F., Krumenauer, M., Reis De Medeiros, D., Oliveira, M.F., Fonseca Tutikian, B., 2017. Desarrollo de contrapiso de hormigón ligero con agregados reciclados de etileno acetato de vinila (EVA) para reducir el impacto sonoro en sistemas de pisos. DYNA 84, 290–295. https://doi.org/10.15446/dyna.v84n201.61491.

Penn, R., Friedler, E., Ostfeld, A., 2013. Multi-objective evolutionary optimization for greywater reuse in municipal sewer systems. Water Res. 47, 5911–5920. https://doi.org/10.1016/j.watres.2013.07.012.

Pradhan, S., Al-Ghamdi, S.G., Mackey, H.R., 2019. Greywater recycling in buildings using living walls and green roofs: a review of the applicability and challenges. Sci. of Total Environ. 652, 330–344. https://doi.org/10.1016/J.SCITOTENV.2018.10.226 Elsevier.

Resende, J.D., Nolasco, M.A., Pacca, S.A., 2019. Life cycle assessment and costing of wastewater treatment systems coupled to constructed wetlands. Resour. Conserv. Recycl. 148, 170–177. https://doi.org/10.1016/j.resconrec.2019.04.034.

Roebuck, R.M., Oltean-Dumbrava, C., Tait, S., 2011. Whole life cost performance of domestic rainwater harvesting systems in the United Kingdom. Water Environ. J. 25, 355–365. https://doi.org/10.1111/j.1747-6593.2010.00230.x.

Şahin, N.İ., Manioğlu, G., 2019. Water conservation through rainwater harvesting using different building forms in different climatic regions. Sustain. Cities Soc. 44, 367–377. https://doi.org/10.1016/j.scs.2018.10.010.

Scheepens, A.E., Vogtländer, J.G., Brezet, J.C., 2016. Two life cycle assessment (LCA) based methods to analyse and design complex (regional) circular economy systems. Case: making water tourism more sustainable. J. Clean. Prod. 114, 257–268. https://doi.org/10.1016/j.jclepro.2015.05.075.

Scheuer, C., Keoleian, G.A., Reppe, P., 2003. Life cycle energy and environmental performance of a new university building: modeling challenges and design implications. Energy Build. 35, 1049–1064. https://doi.org/10.1016/S0378-7788(03)00066-5.

Silva, C.M., Sousa, V., Carvalho, N.V., 2015. Evaluation of rainwater harvesting in Portugal: application to single-family residences. Resour. Conserv. Recycl. 94, 21–34. https://doi.org/10.1016/j.resconrec.2014.11.004.

Stec, A., Kordana, S., 2015. Analysis of profitability of rainwater harvesting, gray water recycling and drain water heat recovery systems. Resour. Conserv. Recycl. 105, 84–94. https://doi.org/10.1016/j.resconrec.2015.10.006.

Stephan, A., Stephan, L., 2017. Life cycle water, energy and cost analysis of multiple water harvesting and management measures for apartment buildings in a Mediterranean climate. Sustain. Cities Soc. 32, 584–603. https://doi.org/10.1016/j.scs.2017.05.004.

Tavakol-Davani, H., Goharian, E., Hansen, C.H., Tavakol-Davani, H., Apul, D., Burian, S.J., 2016. How does climate change affect combined sewer overflow in a system benefiting from rainwater harvesting systems? Sustain. Cities Soc. 27, 430–438. https://doi.org/10.1016/j.scs.2016.07.003.

Unami, K., Mohawesh, O., Sharifi, E., Takeuchi, J., Fujihara, M., 2015. Stochastic modelling and control of rainwater harvesting systems for irrigation during dry spells. J. Clean. Prod. 88, 185–195. https://doi.org/10.1016/j.jclepro.2014.03.100.

Wang, R., Zimmerman, J.B., 2015. Economic and environmental assessment of office building rainwater harvesting systems in various U.S. Cities. Environ. Sci. Technol. 49, 1768–1778. https://doi.org/10.1021/es5046887.

Wanjiru, E., Xia, X., 2017. Optimal energy-water management in urban residential buildings through grey water recycling. Sustain. Cities Soc. 32, 654–668. https://doi.org/10.1016/j.scs.2017.05.009.

World Bank. World Development Report 2020: Trading for Development in the Age of Global Value Chains. World Bank Publications, Washington, DC, p. 1457. https://doi.org/10.1596/978-1-4648-.

Zhang, X., Zhang, M., Zhang, H., Jiang, Z., Liu, C., Cai, W., 2020. A review on energy, environment and economic assessment in remanufacturing based on life cycle assessment method. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2020.120160.

Zink, T., Geyer, R., 2017. Circular economy rebound. J. Ind. Ecol. 21, 593–602. https://doi.org/10.1111/jiec.12545.