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Environmental assessment of combined sewer overflow treatment using a vertical-flow constructed wetland: Freshwater saving, water reuse and carbon sequestration co-benefits

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ABSTRACT

Climate change, rapid urbanisation, and intense precipitation are overloading conventional urban sewer systems. Constructed wetlands (CWs), as nature-based solutions, offer a sustainable alternative for treating combined sewer overflows (CSOs). This study evaluates the environmental impacts associated with the construction and operation of a vertical-flow (VF) CW system designed to treat CSOs in southern Chile using the Life Cycle Assessment (LCA) framework. Carbon sequestration, an ecosystem service, was also estimated using a wetland-adapted RothC model coupled with a 500-year spin-up initialisation to equilibrate the carbon pools. Furthermore, a Water Reuse Credit (WReC) is proposed to link reclaimed water reuse with potential freshwater savings while accounting for regional water scarcity using the AWARE method. Results indicate a global warming impact of 0.49 kg CO_2 eq per m^3 of reclaimed water produced, with the construction phase as the main environmental hotspot. Overall, the environmental impacts are consistent with values reported in the literature. Annual physical freshwater substitution was estimated at 1209.3 m^3 yr^{-1}. The corresponding AWARE-weighted saving was 824.7 m^3 world-eq yr^{-1}, reflecting the consideration of water scarcity in the assessment. In addition, a net SOC stock increase equivalent to 0.0051 t CO_2 ha^{-1} yr^{-1} was estimated. Overall, integrating life cycle impacts, water scarcity, and carbon storage highlights the multiple environmental benefits of VF-CWs for CSO treatment and supports context-specific assessment of water reuse and green infrastructure strategies.

1. Introduction

Climate change, population growth, and increasingly intense precipitation events are intensifying the challenges of urban wastewater and stormwater management, pushing aging infrastructure beyond its design capacity [1]. In many urban areas, combined sewer systems become critically overloaded during heavy rainfall. This leads to a situation in which untreated wastewater and stormwater are intermittently discharged directly into rivers, lakes, and coastal waters through combined sewer overflows (CSOs) whenever rainfall intensity exceeds the capacity of the urban sewer system [2]. These events deteriorate water quality, threaten aquatic ecosystems and public health, and compromise essential ecosystem services [3].

Conventional "grey" infrastructure solutions, such as expanding sewer networks or stormwater tanks, often present elevated costs, high energy demands, and a significant carbon footprint due to the intensive use of construction materials and substantial operational processes [4]. This has catalysed a paradigm shift in urban water management towards sustainable, decentralised, and nature-based solutions (NbS). These technologies aim to work with natural processes, enhancing resilience and providing co-benefits beyond water treatment, such as helping to address biodiversity loss and supporting climate change mitigation [5].

Constructed wetlands (CWs) represent one of the most widely implemented NbS for different types of wastewater, including CSOs, as

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well as stormwater treatment. CWs mimic the processes of natural wetlands for efficient water treatment through a combination of physical, chemical, and biological mechanisms involving vegetation, substrates, and microbial communities [6,7]. Beyond water treatment, these systems also provide ecosystem services, including enhancing urban biodiversity, supporting groundwater recharge, and potentially contributing to soil organic carbon sequestration through the accumulation of organic matter in the wetland substrate [8,9].

Agriculture accounts for up to 70% of freshwater withdrawal volumes [10], dominating freshwater use globally and playing a major role in exacerbating water scarcity, particularly in water-stressed regions [11]. In this context, CWs can also act as a link between urban water management and agricultural water demand, enabling water reuse strategies that extend beyond the urban drainage system. CWs allow the reclamation of water suitable for agricultural irrigation, relieving pressure on freshwater resources (whether groundwater or water intended for human consumption), and reducing demand for synthetic fertilisers. By substituting conventional irrigation with reclaimed water from CWs, these systems can help not only to alleviate competition for freshwater resources but also to contribute to sustainable agricultural practices [12]. Moreover, there is growing interest in developing new metrics to better account for and incentivise water reuse, thereby improving the valuation and governance of this critical resource within sustainability frameworks [13,14].

However, despite the well-documented ecological and social co-benefits, some questions remain: i) *what are the potential environmental impacts associated with the vertical flow constructed wetland (VF-CW) systems for CSO treatment?* and ii) *can the environmental benefit associated with water reuse be quantified more representatively using water scarcity indicators?* To answer these questions, Life Cycle Assessment (LCA) provides a comprehensive and standardised framework to quantify environmental impacts across the life cycle of a product or process, offering a clear basis for designing targeted improvement strategies [15]. This methodology enjoys wide acceptance within the wastewater treatment sector [16], with studies identifying infrastructure-related material inputs, energy requirements, and direct greenhouse gas emissions in CWs as dominant contributors shaping their overall environmental performance [17,18]. Despite these advancements, although reclaimed water can reduce pressure on freshwater resources, the environmental significance of this benefit varies considerably across regions. Saving this resource in a water-abundant watershed does not provide the same environmental benefit as saving water in a water-scarce region. To account for these differences, the Available Water Remaining (AWARE) method [19] was developed to characterise freshwater consumption according to local water scarcity conditions, providing a scientifically robust basis for quantifying the environmental relevance of water conservation and reuse strategies. Furthermore, although the assessment of ecosystem services such as carbon sequestration remains limited in constructed wetlands, such an assessment could help demonstrate their potential contribution to the net carbon balance during operation and their capacity to offset a portion of greenhouse gas (GHG) emissions when applied in the agricultural sector.

Having outlined this context, the aim of this study is to evaluate the environmental performance of a VF-CW designed to treat CSOs for reclaimed water supply in southern Chile. This country is one of the most water-stressed in Latin America, driven by prolonged drought conditions (e.g., rainfall declining by up to 30%), and increasing anthropogenic demand, with 39% of the country affected by abnormally dry or drought conditions in 2024 [20]. We hypothesise that the environmental benefit of freshwater savings achieved through water reuse depends on the degree of water stress in the region where the reclaimed water is supplied. To investigate this, we propose a Water Reuse Credit, a novel metric designed to quantify the benefit of freshwater substitution by integrating the volume of reclaimed water supplied with regional water scarcity conditions. The WReC combines established approaches, including system expansion, AWARE 2.0 characterisation, and water valuation based on a shadow price, into a single metric specifically designed to assess the benefits of water reuse. Unlike a conventional AWARE-weighted water scarcity footprint, which characterises the potential impacts associated with water consumption, the WReC quantifies the benefit of freshwater substitution and enables this to be considered alongside the environmental impacts of the treatment system. Furthermore, because the environmental benefits of constructed wetlands extend beyond wastewater treatment and water reuse, we also apply a wetland-adapted RothC model to estimate soil organic carbon accumulation. Finally, this study addresses a geographical and thematic gap in the literature, as relatively few studies have investigated constructed wetlands in South America, particularly for CSO treatment. By integrating water reuse benefits, treatment-related environmental impacts and carbon accumulation, this study provides an exploratory framework for a more comprehensive assessment of the environmental performance of constructed wetlands.

2. Materials and methods

2.1. Vertical flow constructed wetland system as case study

This study addresses a VF-CW system designed and evaluated for treating CSO in southern Chile based on the work by Vera-Puerto et al. [21]. The pilot-scale system consisted of three parallel wetland units with a combined surface area of 17.28 m^2. The filter media included a 0.6 m layer of sand between layers of gravel, and the beds were planted with *Schoenoplectus americanus*, a native wetland species. The system was operated at a nominal outflow rate of 0.03 L s^{-1} m^{-2}, corresponding to a total flow rate of 1.866 m^3 h^{-1}. Each treatment event lasted 72 h, simulating typical CSO discharge durations following storm events. Assuming nine operational events per year over a 20-year lifespan, the total volume of CSO treated by the system is estimated at 24,186 m^3. More information about the experimental system and its operation can be found in Vera-Puerto et al. [21].

In terms of performance, the VF-CW system demonstrated high removal efficiencies for suspended solids (93%) and organic matter (84% for BOD_5 and 86% for COD). Total phosphorus removal averaged 55%, largely attributed to the calcium-rich sand used in the filter media. However, pathogen removal was limited, achieving only slightly more than a 1-log reduction of *E. coli*, indicating a need for supplementary disinfection. The composition of the reclaimed water after CW treatment is presented in Table 1.

For its subsequent use in agricultural irrigation and to comply with Chilean legislation, it is necessary to reduce faecal coliform concentrations to $\leq$1000 CFU/100 mL [22]. As this process was not addressed during the pilot-scale experiment, and to consider all steps needed for the proper operation of the system, the ozonation treatment proposed by Tondera et al. [23] was included to account for all treatment steps required for the safe reuse of the reclaimed water. This treatment considers a dose of 10 mg L^{-1} and a contact time of 15 min to achieve a reduction of approximately 3.4 logarithmic units in the concentration of this pathogen.

In the watershed under analysis, irrigated agriculture includes crops with high water requirements, which contribute substantially to overall agricultural water demand. Potatoes, one of the main crops in southern

Table 1
Composition of the reclaimed water obtained from the constructed wetland.

Parameter	Value	Unit
COD	48.5	mg L^{-1}
BOD_5	20	mg L^{-1}
Total nitrogen	21.5	mg L^{-1}
Total phosphorus	4.3	mg L^{-1}
Total suspended solids	14.8	mg L^{-1}

COD: Chemical Oxygen Demand; BOD_5: 5-day Biochemical Oxygen Demand.

Chile, require less than 400 m^3 of water per ton of product, whereas berries can exceed 1300 m^3 ton^{-1} [24].

2.2. Life cycle assessment

To determine the potential environmental impacts of the VF-CW, the four phases of LCA according to ISO 14040 and ISO 14044 were followed [25,26]: i) goal and scope definition, ii) life cycle inventory, iii) life cycle impact assessment and iv) interpretation.

2.2.1. Definition of goal and scope

This manuscript investigates the potential environmental impacts of a VF-CW designed to treat CSO, followed by an ozonation stage that enables safe irrigation reuse, thus contributing to freshwater demand reduction in the region. For this purpose, a functional unit (FU) of 1 m^3 of treated CSO effluent suitable for irrigation was selected, as the primary function of the system is the treatment of CSO [27].

An attributional LCA was conducted following a cradle-to-gate approach, which is commonly applied in the analysis of wastewater treatment technologies, and particularly in CW systems [28]. This scope includes all environmental impacts associated with the construction and operation stages of CW system, starting from the extraction and production of raw materials required for its construction and operation ("cradle") up to the point where the reclaimed water leaves the ozonation stage ("gate") (see Fig. 1). Subsequently, a scenario-based assessment was performed separately from the core LCA system boundary to estimate the potential environmental benefit associated with freshwater substitution through agricultural reuse.

2.2.2. Life cycle inventory

Table 2 presents the life cycle inventory (LCI) of the treated CSO effluent. Although the N and P contained in the treated effluent could provide nutrient inputs under subsequent irrigation reuse, the post-treatment irrigation stage and its effects on soil and crops are outside the system boundary considered in this study. Therefore, the residual N and P in the treated effluent are accounted for as emissions to water at the system outlet. Energy requirements for pumping and auxiliary equipment were obtained from primary operational data collected through questionnaires at the pilot plant. Construction material inventories were compiled from procurement invoices associated with the installation of the treatment system, while process water consumption and operational inputs were based on data reported in previous studies [21]. The operational data correspond to the year 2024. Secondary data, corresponding to the background system (e.g., infrastructure or chemicals production), were extracted from the Ecoinvent® database version 3.10 [29]. The specific background processes used in the LCA model are listed in **Table S1** of the Supplementary Materials (SM). The SimaPro

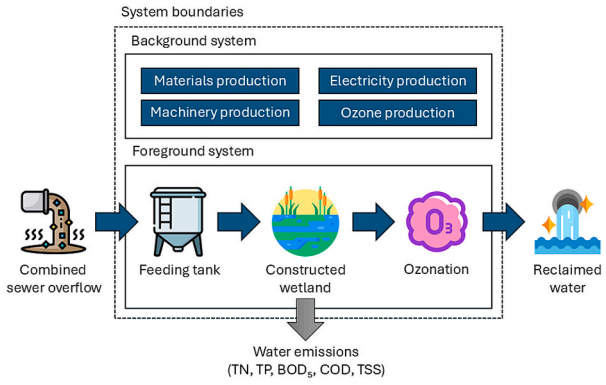


Fig. 1. System boundaries of the constructed wetland. TN: Total nitrogen; TP: Total phosphorus; BOD_5: 5-day Biological Oxygen Demand; COD: Chemical Oxygen Demand; TSS: Total Suspended Solids.

Table 2
Inventory data of vertical flow constructed wetland (per m^3 of treated CSO effluent suitable for irrigation).

Inputs			Outputs		
Item	Value	Unit	Item	Value	Unit
Excavator	8.05	s	*Products*		
Copper	6.95	g	Reclaimed water	1	m^3
PVC (wire)	4.40	g	*Emissions to water*		
Gravel	0.36	dm^3	COD	48.5	g
Sand	0.43	dm^3	BOD_5	20.0	g
Wood	0.11	dm^3	TSS	14.8	g
Steel	8.69	g	TN	21.5	g
PVC (pipes)	13.90	g	TP	4.30	g
PVC (others)	0.47	g	*Avoided emissions*		
Concrete	0.29	dm^3	COD	306.1	g
Adhesive	0.02	cm^3	BOD_5	108.6	g
PU silicone	0.10	cm^3	TSS	194.7	g
HDPE	0.01	dm^3	TN	8.40	g
Electricity	46.4	Wh	TP	5.30	g
Ozone	10.0	g			

COD: Chemical Oxygen Demand; BOD5: 5-day Biochemical Oxygen Demand; TSS: Total Suspended Solids; PVC: Polyvinylchloride; PU: Polyurethane; HDPE: High Density Polyethylene.

v10.2.0.1 software [30] was used to implement the inventory data.

An uncertainty analysis was carried out on the inputs obtained from the Ecoinvent® database. The Monte Carlo simulation was performed in SimaPro® software with 1000 iterations and a 95% confidence interval to propagate the uncertainties and assess their impact to the results, which are presented in **Table S2** in the SM. For the input data, the distribution used was log-normal, with deviations estimated based on default values from Ecoinvent® database.

2.2.3. Life cycle impact assessment

The environmental impacts were evaluated using a selection of impact categories from the ReCiPe 2016 Midpoint (H) V1.11 / World (2010) H method [31]. The analysed impact categories were: Global Warming (GW), Stratospheric Ozone Depletion (SOD), Fine Particulate Matter Formation (FPMF), Terrestrial Acidification (TA), Freshwater Eutrophication (FE), Marine Eutrophication (ME), Human Carcinogenic Toxicity (HCT), Land Use (LU), Mineral Resource Scarcity (MRS), and Fossil Resource Scarcity (FRS). These impact categories were selected considering their importance in terms of impact to the freshwater compartment (e.g., freshwater eutrophication) and other environmental pressures, such as climate change or toxicity impacts, that are widely adopted in LCA evaluations of nature-based solutions for wastewater treatment systems [17,32]. An additional freshwater compartment impact category, water scarcity, was assessed using the AWARE characterisation method [33], as it is considered a consensus model to evaluate water removals in life cycle impact assessment (see Section 2.3 for more details). For each impact category, the inventory flows were characterised using the corresponding characterisation factors of the selected method, and the resulting impact scores were calculated per functional unit.

2.3. Water reuse credit

Recent research shows that many river basins in Chile have experienced increasing water stress, with semi-arid regions exhibiting high to extreme water scarcity due to prolonged drought and elevated water demand, especially from agriculture and land-use changes [34]. The potential benefits of replacing freshwater abstraction with reclaimed water for irrigation process were quantified using a water scarcity-based indicator consistent with ISO 14046 principles [35]. Water use was expressed as consumptive water use, defined as water withdrawn and not returned to the same watershed at comparable quality. A 1:1 substitution was assumed, whereby 1 m^3 of reclaimed water replaces 1 m^3

of freshwater for irrigation. This substitution follows a system expansion approach consistent with ISO 14044, on the basis that reclaimed water provides the same irrigation function as freshwater [26]. This assumption represents a potential water reuse scenario based on the treated water meeting Chilean regulatory quality requirements, rather than a specific irrigation application. Therefore, no specific crop, irrigation schedule, storage infrastructure, or distribution system is assumed.

To calculate the water saving factor for the CW (WSF_{CW}), the annual volume of reclaimed water (V_{RW}) produced (1209.3 m^3 yr^{-1}) is multiplied by the specific water scarcity (i.e., AWARE 2.0) characterisation factor [33] of the wetland's watershed (CF_{AWARE}), as shown in Eq. 1. The AWARE 2.0 characterisation factors used for the watershed evaluated in this study, together with those for other representative watersheds in the region, are presented in **Table S3** of the SM. The specific annual AWARE characterisation factor for the watershed is 0.682 m^3 world-eq m^{-3} [19].

$$WSF_{CW} = V_{RW} \times CF_{AWARE} \quad (1)$$

where WSF is the water saving factor (m^3 world-eq yr^{-1}), V_{RW} is the annual volume of reclaimed water (m^3 yr^{-1}), and CF_{AWARE} is the AWARE 2.0 characterisation factor (m^3 world-eq m^{-3}) corresponding to the relevant river basin in Chile. The AWARE characterisation factor quantifies the relative amount of water remaining available per area after satisfying both human and ecosystem water demands [33]. Higher values of this factor indicate greater water scarcity, implying greater environmental relevance of water saving. Multiplying the annual reclaimed water volume by this factor yields the AWARE-weighted water saving, accounting for the local water scarcity conditions.

Once the water saving-based factor was calculated, the water reuse credit ($WReC$) was estimated by multiplying it by the shadow price of water (SP_W) for agricultural use, as shown in Eq. 2. Inspired by the concept of carbon credits, the $WReC$ represents a time-dependent environmental and economic benefit associated with freshwater substitution over the operational lifetime of the VF-CW, rather than a permanent or tradable credit.

$$WReC = WSF_{CW} \times SP_W \quad (2)$$

where $WReC$ is the water reuse credit (US$ world-eq yr^{-1}), WSF is the water saving factor (m^3 world-eq yr^{-1}), and SP_W is the shadow price of water (US$ m^{-3}). Here, the shadow price is applied as a valuation parameter to the AWARE-weighted water saving factor, rather than as a direct price of physical water. Thus, WReC represents a scarcity-weighted economic-equivalent value (US$ world-eq yr^{-1}), rather than a direct monetary valuation of the physical volume of reclaimed water. The central estimate of this shadow price is US$0.50 per m^3 [36], representing a literature-based average for irrigation water that incorporates scarcity rents and externalities along the water value chain. As this value is derived from multiple studies rather than being site-specific, it was adopted as a common reference to monetise water savings across all evaluated watersheds. This parameter translates physical water savings into an economic-equivalent metric, enabling comparison of water reuse benefits under contrasting water scarcity conditions. Variations in local economic conditions and water valuation were explored through sensitivity analysis.

2.4. Carbon sequestration model

Carbon sequestration in the VF-CW substrate was simulated using a modified version of the Rothamsted Carbon Model (RothC) [37], specifically adapted for wetland ecosystems following the framework described by Bohaienko et al. [38]. RothC was selected because it is one of the most widely validated and extensively applied models for simulating long-term soil organic carbon dynamics under different climate, soil, and land-use conditions [39]. However, as the original model was developed for well-drained aerobic soils, its application to constructed wetlands requires modifications to account for prolonged water saturation, reduced decomposition rates, and methane production under anaerobic conditions. The model was implemented in a Python 3.14 environment. To accurately reflect the biogeochemical dynamics of the experimental VF-CW in southern Chile, two major adaptations were integrated into the decomposition engine [38]:

- Anoxia modification factor: A hydrological control function that inhibits microbial decomposition as the substrate reaches saturation, following the bimodal response to moisture characteristic of wetlands. The function was driven by a monthly water level input ranging from 0 to 1, used directly as the relative water content (θ) in the model.
- Mineralised carbon partitioning: A function was implemented to partition carbon allocated to gaseous emissions between CO_2 and CH_4, following the approach of Bohaienko et al. [38]. The saturated fraction was estimated from the normalised water level ($f_{sat} = \theta$), with carbon associated with saturated conditions partitioned between CO_2 and CH_4 using ($\omega = 0.75$).

Model input data, including substrate properties, climatic variables, and vegetation characteristics, are summarised in **Table S4** of the SM. The initial Inert Organic Matter (IOM) was estimated using the equation proposed by Falloon et al. [40] (Eq. 3):

$$IOM = 0.049 \cdot (TOC)^{1.139} \quad (3)$$

where IOM is the initial inert organic matter (t C ha^{-1}), and TOC is the total organic carbon content (t C ha^{-1}). The initial TOC was established at 17.5 g C kg^{-1} [41], a representative value for CW substrates. Based on a bulk density of 1.72 g cm^{-3} and an active sand layer depth of 0.6 m, this concentration physically scales to an initial baseline TOC stock of approximately 180.6 t C ha^{-1}. Introducing this stock value into Eq. 3 yields an initial IOM stock of approximately 18.2 t C ha^{-1}.

To prevent mathematical artifacts from empty pools, a 500-year spin-up was performed using the monthly input sequence repeated throughout the spin-up period. Due to the lack of experimental pool data, the model was run under baseline climate and plant inputs, and the resulting active pools were used as the initial state for the definitive simulation. The resulting initial soil organic carbon (SOC) stock was 56.29 t C ha^{-1}.

Model outputs included the main carbon pools — decomposable plant material (DPM), resistant plant material (RPM), microbial biomass (BIO), humified organic matter (HUM), inert organic matter — as well as SOC and gaseous carbon emissions. The IOM pool remained constant throughout the simulation period, as defined in the model structure.

3. Results and discussion

3.1. Environmental impact analysis

The environmental impacts associated with the VF-CW throughout its lifespan are shown in Table 3. In addition, Fig. 2 shows the distribution of impacts between those associated with the operation of the VF-CW and those linked to its construction. The machinery category reflects the impacts from the use of earthmoving and site-preparation equipment; construction includes the impacts associated with all construction materials; gravel and sand correspond to the formation of the respective filtration layers within the wetland; the operation stage accounts for the system's electricity consumption and water emissions; and the ozonation stage represents the impact associated with the applied ozone dose. The operation stage also includes avoided emissions resulting from wastewater treatment, which prevents the direct discharge of untreated water into the environment. This generates an environmental credit (negative impact) in the FE category, as the amount of avoided phosphorus emissions exceeds the impacts associated with the operation of the treatment system. The simulated emissions estimated by the modified

Table 3
Environmental results per cubic meter of treated CSO effluent suitable for irrigation.

Impact category	Value	Unit
GW	0.49	kg CO_2 eq
SOD	0.21	mg CFC_{11} eq
FPMF	2.25	g $PM_{2.5}$ eq
TA	2.4	g SO_2 eq
FE	−2.32	g P eq
ME	3.91	g N eq
HCT	0.13	g 1,4-DCB
LU	0.74	m^2a crop eq
MRS	4.25	g Cu eq
FRS	138.9	g oil eq

GW: Global warming; SOD: Stratospheric ozone depletion; FPMF: Fine particulate matter formation; TA: Terrestrial acidification; FE: Freshwater eutrophication; ME: Marine eutrophication; HCT: Human carcinogenic toxicity; LU: Land use; MRS: Mineral resource scarcity; FRS: Fossil resource scarcity.

RothC model were not included in the inventory and, consequently, is not reflected in the GW results reported in Table 3.

The main hotspot of the system in almost all analysed impact categories corresponds to the construction stage of the VF-CW, with contributions ranging from 40% in FRS to as much as 99% in LU and MRS. The only exceptions are the eutrophication categories, where the relative contribution of the construction stage is reduced because the operation stage is largely driven by phosphorus and nitrogen emissions (and their associated avoided emissions), which dominate these impact categories. Consequently, the operation stage becomes the main hotspot. In FE, avoided phosphorus emissions resulting from wastewater treatment generate an environmental credit, contributing up to −85% of the total impact. In contrast, ME is almost entirely driven by nitrogen emissions in the treated effluent, which account for more than 99% of the total impact in this category.

FPMF is primarily driven by upstream emissions associated with the production and transport of construction materials, rather than by on-site emissions. Emissions of particulate matter smaller than 2.5 μm account for 69% of the total impact, followed by sulphur dioxide and nitrogen oxides, contributing 21% and 9%, respectively. Conversely, in the GW and SOD indicators, the impacts are largely dominated by carbon dioxide emissions, accounting for 91% of GW impacts, and by dinitrogen monoxide emissions, which contribute 88% of the SOD impacts. In the case of FRS, the contribution is distributed among oil, coal, and natural gas consumption, accounting for 52%, 25%, and 19%, respectively. Moving to TA, the impacts are mainly driven by sulphur dioxide emissions associated with the production of copper used for the electrical wiring. HCT is dominated by formaldehyde (60%) and 2,3,7,8-tetrachlorodibenzo-*p*-dioxin (20%), primarily originating from polyurethane and concrete production. Finally, MRS is dominated by nickel (82%) and iron (7%) associated with steel production, while LU is almost entirely driven by forest occupation for wood production, representing approximately 99% of the total impact.

Within the construction stage, concrete production is responsible for approximately one-third of the GW impacts, followed by the consumption of steel, wood, and PVC, each contributing between 18% and 23%. For SOD, wood consumption is the main contributor, accounting for 38% of the impacts, followed by PVC with 31%. In contrast, for the FRS category, PVC production is the dominant contributor, representing 34% of the impacts, while the remaining materials (copper, sand, etc.) contribute between 19% and 21%. Finally, in the case of FPMF, the impacts are clearly dominated by wood consumption, which accounts for 77% of the total. At the material level, the impacts associated with concrete are primarily driven by cement production, whereas those related to PVC mainly originate from the production of vinyl chloride, an energy-intensive process involving the manufacture of chlorine and ethylene.

In GW, SOD, and FRS, the use of construction machinery contributes significantly to the impacts, mainly due to diesel consumption and machinery transport. Impacts associated with gravel and sand, the layers forming the VF-CW, are practically negligible across all impact categories, not exceeding 6% in any case. This is because the quantities required are well amortised over the total volume of water treated throughout the VF-CW's lifetime. Finally, ozonation contributes between 6% and 23% to most impact categories, mainly due to the electricity required for ozone generation. However, its contribution is negligible in the eutrophication categories, as well as in LU and MRS.

Regarding the consideration of avoided impacts, their influence is particularly evident in FE and ME, as these are directly affected by the avoided nutrient emissions. The inclusion of avoided impacts reduces the overall ME impact by approximately 38.9%, while for FE, the avoided impacts exceed the impacts generated by the system, resulting in a net negative impact. Given the importance of construction materials in the overall environmental profile, a sensitivity analysis was performed by varying the quantities of construction materials and the ozone dose by ±10% (see **Table S5** in the SM), as well as the system lifetime by ±5 years and the annual number of CSO events by ±1 event per year (see **Table S6** in the SM). The sensitivity analysis showed that variations in the quantities of construction materials had a visible effect on FPMF, TA, HCT, LU, and MRS, resulting in changes of approximately 6–9% in the estimated impacts. In contrast, variations in the ozone dose had a limited effect, with changes of around 2% observed for GW, SOD, and

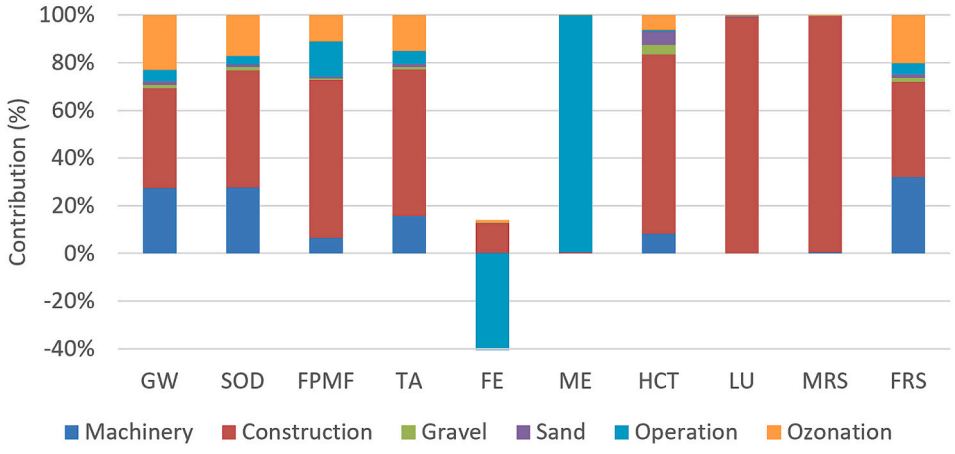


Fig. 2. Main contributors to the overall environmental profile of the constructed wetland. The y-axis is truncated at −40% to improve the visualization of the results. GW: Global warming; SOD: Stratospheric ozone depletion; FPMF: Fine particulate matter formation; TA: Terrestrial acidification; FE: Freshwater eutrophication; ME: Marine eutrophication; HCT: Human carcinogenic toxicity; LU: Land use; MRS: Mineral resource scarcity; FRS: Fossil resource scarcity.

FRS. For the constructed wetland's expected lifetime, a 5-year reduction (25% relative to the initially assumed lifetime) increased impacts by 20–25% across all categories except eutrophication. Similarly, increasing or decreasing the annual number of CSO events by one event resulted in variations of 7–11% across all impact categories except for eutrophication. These results highlight that, although variations in the ozone dose have a limited influence on the environmental profile, the quantities of construction materials, the annual number of CSO events, and the system lifetime are important determinants of the overall environmental impacts.

The Monte Carlo analysis showed relatively low uncertainty for most impact categories (**Table S2**), as reflected by the close agreement between mean and median values and the low standard deviations. GW, SOD, TA, ME, FRS and HCT exhibited coefficients of variation below 15%, indicating robust results despite the uncertainty propagated through the inventory data. In contrast, FPMF, FE, LU and MRS showed higher variability, suggesting greater sensitivity to uncertainty in the background inventory data, (i.e., Ecoinvent processes) contributing to these impact categories.

3.2. Comparison of environmental impacts with other CWs applications

A bibliographic review was conducted to compare our results with those reported for other CWs designed for different types of wastewater treatment. Direct comparisons with previous LCA literature on constructed wetlands should be interpreted with caution due to methodological discrepancies, such as differing system boundaries and operational configurations. A summary of the main characteristics of the studies considered in this comparison, including their functional units, system boundaries, CW types, and main impact results, is provided in Table 4.

Carrillo et al. [17] investigated the environmental impacts associated with the use of monocultures and polycultures in a CW operated for eight years and divided into two seasons (dry and cold) for treating municipal wastewater. The system boundaries included not only the construction and operation of the CW, but also the impacts associated with water pre-treatment stages, such as grit removal, grease removal and a septic tank. In contrast, these pre-treatment stages were not considered in this study because the CSO was collected from the effluent stream of a 10-mm mechanical screen located at the inlet of the full-scale Purranque WWTP. In the GW category, the impacts reported by Carrillo et al. [17] were substantially higher than those obtained in this study, reaching values up to almost 25 times higher for polycultures and between 3 and 16 times higher for monocultures, depending on the season. Similarly, in SOD, Carrillo et al. [17] reported impacts several orders of magnitude higher than those obtained in the present study, with increases of up to a factor of 32. This difference is mainly attributable to methane and nitrous oxide emissions generated in their process, because those authors analysed horizontal subsurface flow CW (HSSF-CW). In HSSF-CW systems, anaerobic conditions are prevalent [43], promoting the formation of these greenhouse gases. In contrast, direct CH_4 and N_2O emissions were not measured in the present study. However, the modified RothC model estimated CH_4 emissions of 0.453 t C ha^{-1} yr^{-1} under the specific hydrological and climatic conditions of the VF-CW. This relatively low CH_4 flux, together with the predominantly aerobic conditions expected in VF-CWs, supports the lower greenhouse gas emissions reported for vertical-flow compared with horizontal-flow systems [44]. Nevertheless, the absence of direct N_2O measurements remains a source of uncertainty and should be considered when interpreting the GHG results. For FPMF, the impact in the present study was 32% lower than that reported by Carrillo et al. [17], which may be related to differences in electricity consumption, identified as the main hotspot of this category in their study. Regarding eutrophication impact categories, nitrogen emissions to water reported by Carrillo et al. [17] were higher than those in the present study. Finally, in FRS and TA, Carrillo et al. [17] reported higher impacts, which can be explained by the demand for key infrastructure materials. For instance, the higher amount of PVC consumed in the system evaluated by Carrillo et al. [17] contributes substantially to TA due to the release of acidifying precursors (e.g., NO_x and SO_2) during its production.

Lower environmental impacts than those obtained in the present study have been reported for a constructed wetland treating hexachlorocyclohexane-contaminated water in the Czech Republic [42]. The system boundaries included both the construction and operational stages of the technology, comprising a sedimentation unit, an iron filter with biofilters, and an anaerobic compartment. Except for FE, where the inclusion of avoided phosphorus emissions resulted in lower impacts, all impact categories showed lower values than those obtained in our work.

Table 4
Summary of the studies included in the environmental impact comparison, including functional unit, system boundaries, CW type, and main impact results.

Authors	Functional unit	System boundaries	CW type	Main results
This study	1 m^3 of treated CSO effluent suitable for irrigation	Construction and operation of the CW + ozonation step	Pilot-scale VF-CW	Construction of the CW was the main environmental hotspot, contributing 40–99% of impacts in most categories. Operation dominated eutrophication impacts due to nutrient emissions.
Carrillo et al. [17]	1 m^3 of treated wastewater	Construction and operation of the CW, including WW pre-treatment	Pilot-scale HSSF-CW; monoculture and polyculture configurations	Polyculture reduced FE impacts by 5–17% compared with monocultures, but showed the highest GW impacts, 1.5–9 times higher than monocultures.
Bałazińska et al. [42]	1 m^3 of treated water	Construction and operation	Wetland+® technology: combined treatment systems + CW	Lower impacts than the present study in all categories except FE. ME was 21% lower, while FPMF and LU were up to 90% lower and the remaining categories were 53–83% lower.
Alam et al. [32]	1 m^3 of wastewater treated	Construction and operation	Laboratory-scale CW systems with different configurations for industrial wastewater and landfill leachate treatment	GW impacts exceeded 80 kg CO_2 eq m^{-3} and FRS exceeded 12 kg oil eq m^{-3} in the highest-impact configurations. HCT ranged from approximately 0.5 to 4.5 kg 1,4-DCB eq m^{-3}, while FE ranged from 4 to 16 g P eq m^{-3}. Cement mortar and brick were the dominant contributors, accounting for more than 90% of the impacts in most selected categories.
Vassalle et al. [18]	1 m^3 of treated water	Construction and operation	UASB reactor + CW	The UASB + CW scenario showed lower impacts than the present study for GW, SOD, and TA, whereas higher impacts were reported for the remaining categories when avoided impacts from biogas cogeneration were excluded. Construction materials were the main contributors in most impact categories.

CSO: Combined sewer overflow; VF-CW: Vertical flow constructed wetland; WW: Wastewater; HSSF-CW: Horizontal subsurface flow constructed wetland; UASB: Upflow anaerobic sludge blanket; GW: Global warming; SOD: Stratospheric ozone depletion; FPMF: Fine particulate matter formation; TA: Terrestrial acidification; FE: Freshwater eutrophication; ME: Marine eutrophication; HCT: Human carcinogenic toxicity; LU: Land use; FRS: Fossil resource scarcity.

Compared with the present study, the impacts reported by Bałazińska et al. [42] were 21% lower for ME and up to 90% lower for FPMF and LU, while reductions in the remaining impact categories ranged from 53% to 83%. This difference may be attributed to the lower amounts of infrastructure materials demanded or to lower water emissions generated during the process, although this cannot be confirmed due to the lack of detailed inventory data in their study. Regarding the hotspots, the main impacts related to the construction phase were associated with PVC, concrete and zero-valent iron, while those of the operational phase were mainly attributed to electricity consumption. Similarly, in the present study, concrete, and PVC were also identified among the materials contributing most to the overall environmental impacts.

Substantially higher environmental impacts have been reported for laboratory-scale constructed wetlands treating industrial wastewater [32] than those obtained in the present study. The authors evaluated five different CW configurations, varying plant species and flow rate, while including both the construction and operational phases within the system boundaries. Although the impact values are not reported directly, it can be observed that in categories such as GW and FRS, the impacts are notably higher across all systems analysed, exceeding 80 kg CO_2 eq m^{-3} and 12 kg oil eq m^{-3}, respectively, in the worst-case scenario. A similar trend is observed in the remaining categories; for instance, HCT impacts range from approximately 0.5 to 4.5 kg 1,4-DCB eq m^{-3}, while FE values vary between 4 and 16 g P eq m^{-3}. This difference can be attributed to the higher material and energy consumption reported in their inventory data. For example, electricity consumption in their systems ranges from 0.67 to 1.7 kWh m^{-3}, which is 15–37 times higher than in our study, while PVC consumption is 7–82 times higher. The greater electricity demand is explained by the continuous operation of pumps, unlike CWs treating CSOs, where pumping only occurs during heavy rainfall events. Construction materials constituted the main environmental hotspot, with cement mortar and bricks accounting for most of the impacts [32]. A similar trend was observed in the present study, where construction-related impacts are likewise dominated by cement-based materials, particularly concrete, highlighting their importance as the main environmental hotspot during the construction phase.

Finally, Vassalle et al. [18] evaluated CWs as part of a nature-based solution for wastewater treatment, considering both construction and operation stages, while also accounting for avoided impacts derived from biogas cogeneration. When these avoided impacts are excluded, the up-flow anaerobic sludge blanket (UASB) + CW system shows lower impacts than those reported in our study for GW (53%), SOD (95%), and TA (79%) and higher impacts for the remaining categories. This difference can be mainly attributed to the lower consumption of construction materials, which constitutes the principal hotspot in most impact categories; for example, concrete use is approximately 15 times lower than in our system. Conversely, the higher ME values reported for the UASB+CW system can be explained by higher nitrogen emissions to water, with nitrates being the main contributors to this category. Regarding the main contributors, Vassalle et al. [18] report that construction materials represent the dominant hotspot in GW, SOD, TA, FE, and FRS, accounting for 51% to 90% of the total impacts. By contrast, in the FE and ME categories, almost all impacts are driven by emissions to water. Overall, this hotspot analysis follows the same trend as that reported in the present study.

Therefore, it can be concluded that the proposed VF-CW system for CSO treatment and reclaimed water production presents environmental impacts that are generally lower than those reported in most of the reviewed studies. Most of the impacts are associated with the construction phase of the CW, while its operation generally contributes less to the overall environmental burden.

3.3. Water reuse credit calculation

Agriculture remains the largest consumer of water in Chile, accounting for most of the consumptive use, which further exacerbates water stress conditions in regions with limited water availability [34]. In this context, quantifying the environmental value of reclaimed water becomes particularly relevant, as freshwater savings are expected to provide greater benefits in water-scarce basins than in water-abundant regions.

The physical volume of reclaimed water potentially substituting freshwater is 1209.3 m^3 yr^{-1}. When weighted by the AWARE 2.0 characterisation factor of the study watershed (0.682 m^3 world-eq m^{-3}), this corresponds to a water saving factor of 824.7 m^3 world-eq yr^{-1}. The latter represents a scarcity-weighted water saving and should not be interpreted as the physical volume of freshwater avoided. Although this amount may seem modest in absolute terms, its environmental significance strongly depends on local water scarcity. For example, the same physical water saving would generate a substantially higher WReC in a highly water-stressed basin (e.g., CF $\geq$ 20) than in a water-abundant basin (CF $\approx$ 0.1). This context dependency represents one of the main strengths of the proposed metric, as it assigns greater environmental relevance to freshwater substitution where water resources are under greater pressure. Furthermore, the annual physical water volume of 1209.3 m^3 would support the production of more than 2.9 t of potatoes, whereas it would support slightly more than 0.7 t of berries [24], illustrating how the same reclaimed water volume may support different agricultural systems depending on crop water demand.

Translating these results into economic terms, the WReC corresponds to an economic-equivalent value of approximately US$412 yr^{-1}, obtained by applying the shadow price to the AWARE-weighted water saving factor. This value represents a scarcity-weighted economic-equivalent benefit rather than a direct monetary valuation of the physical volume of freshwater avoided. Although this value is modest at the farm scale, its potential increases considerably under more water-scarce conditions. To demonstrate this effect, a sensitivity analysis was conducted by applying watershed-specific AWARE 2.0 characterisation factors representative of contrasting hydroclimatic conditions in Chile together with a range of shadow prices for irrigation water. Fig. 3 illustrates the resulting variation in the estimated WReC. As expected, WReC increased under both higher water scarcity and higher shadow prices, reaching substantially greater values in water-scarce regions such as the Elqui, Maipo, and Maule valleys than in humid watersheds such as Purranque and Aysén. These findings suggest that the proposed WReC framework can be applied across different geographical contexts and that its environmental and economic equivalent value increases where freshwater conservation is most needed.

Direct comparisons with other studies are limited, which reflects the limited application of approaches that explicitly incorporate water scarcity into the quantification of reclaimed water benefits. The proposed WReC addresses this methodological gap by incorporating the spatial variability of water scarcity into the assessment of freshwater substitution. This enables reclaimed water benefits to be expressed as a standardised indicator that could support future incentive mechanisms and investment prioritisation. Moreover, such an approach is particularly relevant in Chile, where the lack of a comprehensive regulatory framework for water reuse remains one of the main barriers to large-scale implementation [45]. Beyond Chile, the proposed WReC approach could also be applied in other water-scarce regions, where it may provide information relevant to the development of economic incentives or payment schemes that recognise the environmental benefits of freshwater conservation through water reuse.

In the present study, the baseline corresponds to the discharge of CSO without water reclamation, whereas the project scenario produces reclaimed water that could potentially substitute conventional freshwater used for irrigation, thereby providing a clear basis for quantifying avoided freshwater abstraction. Likewise, additionality is supported by three complementary criteria: (i) reclaimed water is only produced through the CW (technical additionality); (ii) water reuse is not currently mandatory under the Chilean regulatory framework

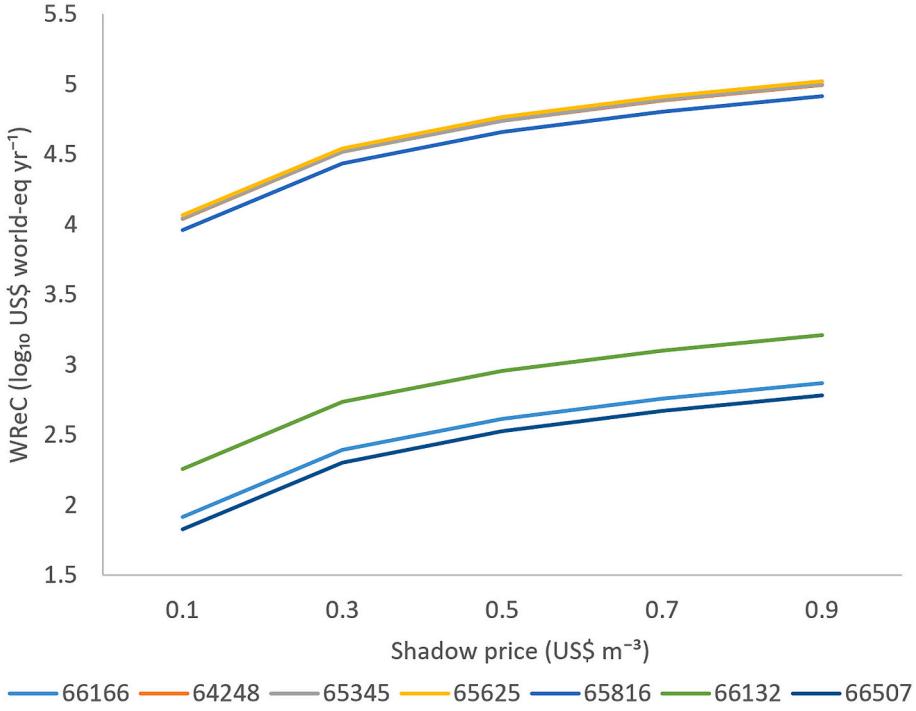


Fig. 3. Sensitivity analysis of the water reuse credit under different watershed-specific AWARE 2.0 characterisation factors and irrigation water shadow prices. 66166: Analysed CW watershed; 64248: Elqui Valley; 65345: Maipo Valley; 65625: Maule Valley; 65816: Biobío Basin; 66132: Valdivia/Los Lagos Region; 66507: Aysén.

(regulatory additionality) [46]; and (iii) the investment and operational costs associated with the CW provide an economic basis for considering an incentive linked to water conservation (economic additionality).

Regarding permanence, the water benefit occurs while freshwater extraction is avoided, making this concept more complex for water than for carbon credits, since CO_2 can remain stored for decades. Thus, permanence could be redefined as the capacity of the system to maintain water savings throughout its useful life, for example, by operating the wetland for 20 years with constant production of reclaimed water. Furthermore, reducing water extraction in one region may cause an increase in extraction in another (rebound effect) [47,48]. As a hypothetical example, a farmer that uses 1000 m^3 of reclaimed water may expand the cultivated area, consuming an additional 800 m^3 of freshwater (net savings of 200 m^3). Therefore, a water credit scheme should monitor changes in land use and water demand. The proposed WReC is intended as an environmental and economic valuation framework rather than as a tradable or regulatory water-credit scheme. Its application is subject to the assumptions underlying freshwater substitution, water valuation, and the potential rebound effects discussed above.

Conventional LCA studies generally account for reclaimed water through avoided-burden or system expansion approaches [49,50], whereby freshwater demand is substituted by reclaimed water supply. The proposed WReC builds upon this established logic by incorporating the spatial variability of water scarcity through the AWARE 2.0 characterisation factor, providing a standardised indicator of the environmental and economic significance of water reuse.

3.4. Carbon sequestration

Following the 500-year spin-up [51], total SOC in the wetland substrate reached 56.2911 t C ha^{-1} at the end of the simulation period, compared with an initial SOC stock of 56.2897 t C ha^{-1}. The resulting net carbon stock increase was approximately 0.0014 t C ha^{-1}. The HUM pool represented the major active fraction of total SOC, reaching 26.45 t C ha^{-1} in December (approximately 47.0% of total SOC), while the constant IOM pool represented 18.2 t C ha^{-1} (approximately 32.3%). These results reflect the modelled balance between organic carbon inputs, decomposition and carbon transfers among the active pools under the simulated conditions.

The SOC stock exhibited seasonal fluctuations alongside changes in the distribution of active carbon pools. By the end of the simulation period, resistant plant material reached 10.70 t C ha^{-1}, while microbial biomass and decomposable plant material accounted for 0.71 and 0.23 t C ha^{-1}, respectively. The larger RPM pool compared with the DPM pool indicates that, at the end of the simulation, the amount of carbon in the resistant plant-material fraction was greater than that in the decomposable fraction. Total SOC peaked at 56.67 t C ha^{-1} in September and reached its minimum of 55.86 t C ha^{-1} in March.

Monthly model outputs revealed clear seasonal variations driven by climatic conditions and changes in decomposition efficiency, represented by the anaerobic reduction factor (α_2), which ranged between 0.28 during summer months and 1.0 during winter conditions. Monthly CH_4 emissions ranged from 0.0137 to 0.0570 t C ha^{-1}, while CO_2 emissions ranged from 0.0439 to 0.3989 t C ha^{-1}. Total emissions over the 12-month simulation amounted to 0.4531 t C ha^{-1} as CH_4 and 2.6414 t C ha^{-1} as CO_2. These patterns reflect the combined influence of the modelled temperature and moisture-anoxia modifiers on carbon decomposition and gas partitioning [52].

Using the IPCC AR6 global warming potential of 27 for biogenic CH_4, the simulated emissions corresponded to approximately 9.69 t CO_2 ha^{-1} from CO_2 and 16.31 t CO_2-eq ha^{-1} from CH_4, resulting in total estimated gaseous emissions of approximately 26 t CO_2-eq ha^{-1} over the simulated year. The net SOC increase of 0.0014 t C ha^{-1} corresponds to approximately 0.0051 t CO_2-eq ha^{-1} of carbon retained in the substrate. This stock increase offsets only approximately 0.020% of the estimated gaseous emissions, indicating that the modelled SOC gain is negligible relative to greenhouse gas emissions. These estimates represent the modelled carbon stock change and gaseous emissions, rather than a complete greenhouse gas balance of the wetland system. Assessing SOC dynamics nevertheless contributes to a more comprehensive environmental assessment of VF-CWs for CSO treatment, alongside their roles in wastewater treatment and reclaimed water production.

3.5. Study limitations

Despite the environmental performance observed, several limitations must be considered when interpreting the results. Firstly, the study was conducted at a pilot scale and, therefore, may not fully represent the environmental behaviour of vertical flow constructed wetlands (VF-CWs) at full scale, particularly regarding operational efficiency and long-term maintenance.

The carbon sequestration analysis also has certain limitations. Carbon dynamics were simulated using a modified RothC model driven by a single-year dataset. Although the spinup procedure was used to stabilise the initial carbon pools, it assumes a steady-state baseline under static climate and plant inputs rather than capturing dynamic decadal shifts. Furthermore, due to the lack of site-specific experimental data for individual active fractions, pool partitioning relies on mathematical stabilisation, introducing model uncertainty. In addition, CH_4 emissions were estimated using the modified RothC model, whereas N_2O emissions were neither measured nor explicitly simulated; therefore, the potential contribution of N_2O to the carbon footprint remains an uncertainty.

Finally, the proposed water credit framework constitutes a conceptual approach intended to quantify the environmental value of replacing freshwater with reclaimed water. Although it provides a transparent and reproducible metric based on local water scarcity, further validation and verification procedures must be established before its implementation in actual incentive or compensation mechanisms.

4. Conclusions

This research evaluated a pilot VF-CW coupled with a theoretical ozonation system as a strategy to produce reclaimed water and alleviate pressure on local watersheds by providing water for crop irrigation from an environmental perspective. The main environmental impacts of the VF-CW system were associated with its construction phase and are comparable to, or even lower than, values reported in the literature for similar treatments.

From the perspective of water reuse, the proposed WReC metric provides a quantitative link between reclaimed water reuse, potential freshwater substitution, and the environmental relevance of water savings in relation to regional water scarcity. By combining physical freshwater substitution with AWARE-based weighting, the metric accounts for the fact that the environmental significance of water savings depends on local water scarcity conditions. Crop-specific water-use equivalents further illustrate the potential agricultural relevance of reclaimed water reuse, although these should be interpreted as scenario-based equivalents rather than direct measures of crop production. Overall, WReC offers a complementary basis for assessing water reuse systems and informing future decisions related to freshwater consumption and reclaimed water management.

The application of VF-CWs to CSO treatment has demonstrated the potential to produce reclaimed water while exhibiting a modest modelled net SOC stock increase. Following a 500-year spin-up, the substrate reached a modelled SOC stock of approximately 56.29 t C ha^{-1}. The estimated net SOC increase was equivalent to 0.0051 t CO_2 ha^{-1} yr^{-1}. This increase offsets only approximately 0.02% of the modelled gaseous emissions, indicating that SOC accumulation provides a negligible offset under the simulated conditions. Accounting for these carbon stock changes and gaseous emissions supports a more comprehensive environmental assessment of VF-CWs.

Future research on CWs applied to CSO treatment or other types of wastewaters should consider the use of less impactful construction materials, assess seasonal variability in reclaimed water production and integrate socio-economic factors to evaluate the feasibility and scalability of the design.

Abbreviations

AWARE	Available Water Remaining
BIO	Microbial Biomass
BOD_5	5-day Biochemical Oxygen Demand
CF	Characterisation Factor
COD	Chemical Oxygen Demand
CSO	Combined Sewer Overflows
CWs	Constructed Wetlands
DPM	Decomposable Plant Material
FE	Freshwater Eutrophication
FRS	Fossil Resource Scarcity
FPMF	Fine Particulate Matter Formation
FU	Functional Unit
GHG	Greenhouse Gas
GW	Global Warming
HCT	Human Carcinogenic Toxicity
HDPE	High-Density Polyethylene
HUM	Humified Organic Matter
IOM	Inert Organic Matter
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LU	Land Use
ME	Marine Eutrophication
MRS	Mineral Resource Scarcity
NbS	Nature-Based Solutions
PU	Polyurethane
PVC	Polyvinyl Chloride
RW	Reclaimed Water
RPM	Resistant Plant Material
SOC	Soil Organic Carbon
SOD	Stratospheric Ozone Depletion
SPW	Shadow Price of Water
TA	Terrestrial Acidification
TN	Total Nitrogen
TOC	Total Organic Carbon
TP	Total Phosphorus
TSS	Total Suspended Solids
VF-CW	Vertical-Flow Constructed Wetland
WSF	Water Saving Factor
WReC	Water Reuse Credit

CRediT authorship contribution statement

Adrián Agraso-Otero: Writing – original draft, Visualization, Software, Methodology, Investigation, Conceptualization. **Ismael Vera-Puerto:** Writing – review & editing, Resources, Project administration, Data curation. **Ian Vázquez-Rowe:** Writing – review & editing, Methodology, Investigation. **Sara González-García:** Writing – review & editing, Supervision, Investigation, Funding acquisition. **Ricardo Rebolledo-Leiva:** Writing – review & editing, Supervision, Investigation, Conceptualization.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jwpe.2026.111250.

Data availability

Data will be made available on request.
Wetland-C-RothCadapted (Original data) (GitHub)

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