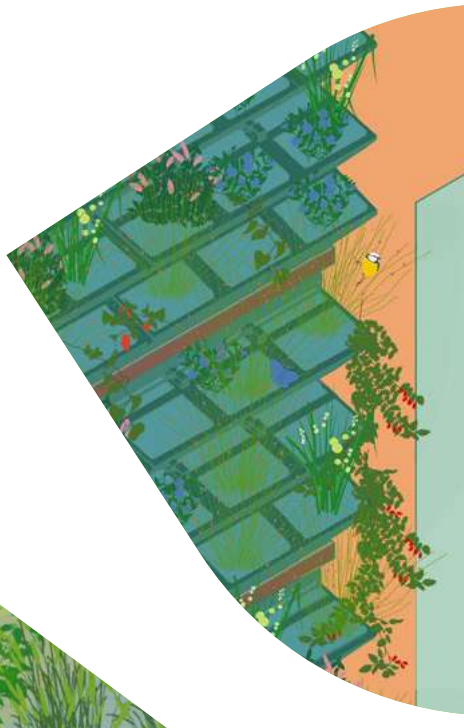




NICE

GUIDELINES FOR DESIGN, IMPLEMENTATION, INTEGRATION & MANAGEMENT OF URBAN INNOVATIVE NBS

including alignment of NICE pilots with IUCN Standard for NbS

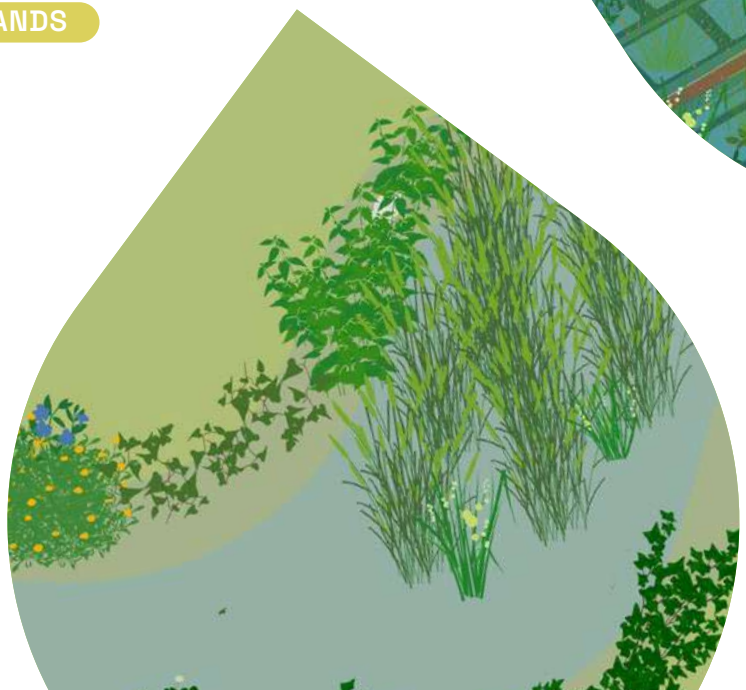


RAIN GARDENS

GREEN WALLS

MULTISTAGE TREATMENT WETLANDS

VERTICAL-FLOW TREATMENT WETLANDS



Funded by
the European Union

Citation

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This document presents the NICE project guidelines for the design, implementation, integration and management of innovative urban nature-based solutions for water treatment and reuse. It translates the knowledge generated in the project's Urban Real Labs into practical guidance that can support the uptake and replication of these solutions in other cities and regions.

The guidelines focus on nature-based solution typologies tested within NICE, including rain gardens, green walls and treatment wetlands for stormwater, greywater and wastewater management. In addition to technical aspects, the document addresses governance, monitoring, maintenance and long-term implementation considerations. The report also demonstrates how the NICE solutions align with the IUCN Global Standard for Nature-based Solutions.

Purpose and scope

The purpose of this document is to support the wider adoption of nature-based solutions for urban water management by making project results accessible to practitioners and decision-makers. The guidelines synthesise key lessons learned, provide recommendations for implementation and highlight enabling conditions for successful deployment and replication.

This document is intended for municipalities, water utilities, planners, engineers, policymakers, researchers and organisations working on climate resilience and sustainable urban development. It can be read as a complete guide or used as a reference for specific typologies and implementation stages.

Target audience

This document is intended for a broad audience involved in urban water management, climate adaptation and sustainable city planning. It is particularly relevant for municipalities and regional authorities, water utilities and infrastructure operators, urban planners and landscape architects, engineers and environmental consultants, policymakers and public agencies, researchers and academic institutions, and organisations working on climate resilience and environmental sustainability.

The guidelines are especially useful for stakeholders exploring innovative and decentralised approaches to stormwater, greywater and wastewater management in urban environments.

How to use these guidelines

These guidelines are designed to be used flexibly according to the reader's needs. They support city authorities, utilities, engineers, policymakers, researchers and practitioners in exploring, planning and implementing nature-based solutions for urban water management, as well as in understanding their benefits and alignment with the IUCN Global Standard. The document can be read in full or consulted as a reference for specific typologies, implementation stages or thematic topics.









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This deliverable provides a comprehensive technical framework to support the replication and upscaling of the innovative Nature-based Solutions (NbS) designed, implemented, and validated within the NICE project. It compiles the full set of technical specifications, design criteria, operational parameters, and performance considerations required to ensure successful transferability to other contexts.

Specifically, the document delivers detailed guidelines for:

- Rain garden systems for stormwater (SW) treatment;
- Green wall systems for greywater (GW) treatment;
- Multi-stage treatment wetlands (TW) for the treatment of greywater and stormwater;
- Vertical-flow treatment wetlands for Combined Sewer Overflow (CSO) treatment;

For each system, the report addresses design principles, dimensioning criteria, material selection, hydraulic and treatment performance considerations, monitoring requirements, and operation and maintenance procedures.

The guidelines are developed taking into account the specific characteristics and constraints of the implementation sites, including water quality parameters, hydraulic loads, climatic conditions, spatial limitations, regulatory context, and relevant environmental and socioeconomic factors.

Furthermore, the deliverable includes a structured assessment of these systems in alignment with the International Union for Conservation of Nature Global Standard for Nature-based Solutions.

The analysis considers the eight core criteria of the framework, ensuring that NICE's NbS pilots meet recognized international standards in terms of environmental integrity, governance, stakeholder engagement, economic viability, and adaptive management.

Within the framework of the NICE project, several innovative NbS were designed, studied, and implemented to treat different types of wastewater (WW), including GW, SW, CSO, and river water. These solutions, primarily consisting of green walls, rain gardens, and treatment wetlands in various configurations, were developed to demonstrate the technical feasibility, environmental benefits, and replicability of NbS across diverse urban contexts.

The **green wall** was specifically investigated for **greywater treatment** during a phase in which operational criteria were developed and subsequently upscaled and implemented under real-world conditions. A pilot system was installed at one of the **Urban Real Labs (URLs)** of the project in **Turin**, specifically in the Cecchi Point building, a community space used by local associations and NGOs. The green wall treats greywater collected from bathroom sinks within the building, enabling its reuse for irrigation of the urban gardens in the courtyard. This pilot has demonstrated the potential of vertical green systems as decentralized, space-efficient solutions for greywater treatment and reuse in dense urban environments. Another similar system was implemented in **Benalmádena**, another URL of the project.

In parallel, an **innovative rain garden research facility** was constructed at the Gdansk University of Technology campus in **Gdansk**. The system integrates multiple stages designed to enhance stormwater purification and manage runoff, incorporating adsorbent materials within the filtration media to improve the removal of specific pollutants commonly present in urban stormwater. Beyond its water treatment function, the rain garden contributes to increased local biodiversity and serves as a multifunctional social space for students, combining ecological, technical, and social benefits within a single pilot installation.

Treatment wetlands were also extensively investigated and implemented in different configurations to address varying treatment objectives within the NICE project. In **Algeciras**, another Urban Real Lab of the project, a multi-stage treatment wetland was implemented for the treatment of greywater and stormwater. Being multi-stage, the first wetland captures greywater from a nearby high school, which is treated to maintain wet operational conditions during dry periods, ensuring system stability and dual functionality. The second wetland system is combined with conventional grey infrastructure (a storm tank). Both systems aim to mitigate pollution associated with sewer overflows during rainfall events in the Bay of Algeciras, while the multi-stage configuration enhances system resilience during periods of water stress.

Finally, a **vertical-flow treatment wetland for Combined Sewer Overflow (CSO) treatment** was implemented at the INRAE REFLET platform in the metropolitan area of **Lyon**, another Urban real Lab. This pilot addresses increasing climate-related pressures, such as heat waves, intense storms, and urban flooding, which challenge the capacity of existing sewer networks. The system is designed to treat either stormwater or combined sewer overflow, depending on the available network connections, contributing to improved urban water resilience and pollution control.



These implementations allowed the project to evaluate the adaptability and performance of hybrid NbS configurations under different climatic, hydrological, and socio-environmental conditions, for multiple purposes, including biodiversity conservation, water reuse, and irrigation of crops.

The guideline typologies included in this deliverable were selected based on identified knowledge gaps and the need for consolidated technical guidance for innovative urban NbS implemented within the NICE project. Conventional wetland systems already covered by extensive international manuals were not prioritized.

Considering this context, the present document includes comprehensive guidelines for the replication of these solutions, supporting their technical, environmental, and social implementation in a variety of urban settings.

1. Introduction and methodology for alignment Standard for Nature-based Solutions

1.1 Introduction

The NICE project is piloting innovative Nature-based Solutions (NbS) to address urban water management challenges, including stormwater, greywater, combined sewer overflows, and river restoration. While these pilots demonstrate technological and ecological innovation, their long-term credibility and replicability depend on adherence to globally recognized standards.

The International Union for Conservation of Nature (IUCN) developed the Global Standard for Nature-based Solutions to provide a common framework for designing, verifying, and scaling interventions that work with nature to address societal challenges. The Standard responds to the growing recognition that protecting, sustainably managing, and restoring ecosystems can deliver measurable benefits for both people and biodiversity, while contributing to climate resilience, resource security, and sustainable development (IUCN, 2020).

NbS are conceived as actions that address major societal challenges, such as climate change, food and water security, disaster risk reduction, and biodiversity loss, through the conservation, restoration or sustainable use of ecosystems. The Global Standard was created to ensure that such interventions are not implemented as isolated green measures, but instead follow a coherent, evidence-based approach that delivers environmental integrity, social equity, and economic viability (IUCN, 2020).

At its core, the Global Standard is structured around eight interrelated criteria and associated indicators that guide NbS interventions across their full life cycle, including aspects such as problem identification and design, governance, financing, adaptive management, and long-term mainstreaming of solutions. The eight criteria are presented in the following table.

Table 1.1

The eight criteria of the IUCN Global Standard for Nature-based Solutions (adapted from IUCN, 2020).

THE EIGHT CRITERIA OF THE IUCN GLOBAL STANDARD FOR NATURE-BASED SOLUTIONS

Criterion 1

NbS effectively addresses societal challenges

Criterion 2

Design of NbS is informed by scale

Criterion 3

NbS result in a net gain to biodiversity and ecosystem integrity

Criterion 4

NbS result in a net gain to biodiversity and ecosystem integrity

Criterion 5

NbS are based on inclusive, transparent, and empowering governance processes

Criterion 6

NbS equitably balance trade-offs between achievement of their primary goal(s) and the continued provision of multiple benefits

Criterion 7

NbS are managed adaptively, based on evidence

Criterion 8

NbS are sustainable and mainstreamed within an appropriate jurisdictional context

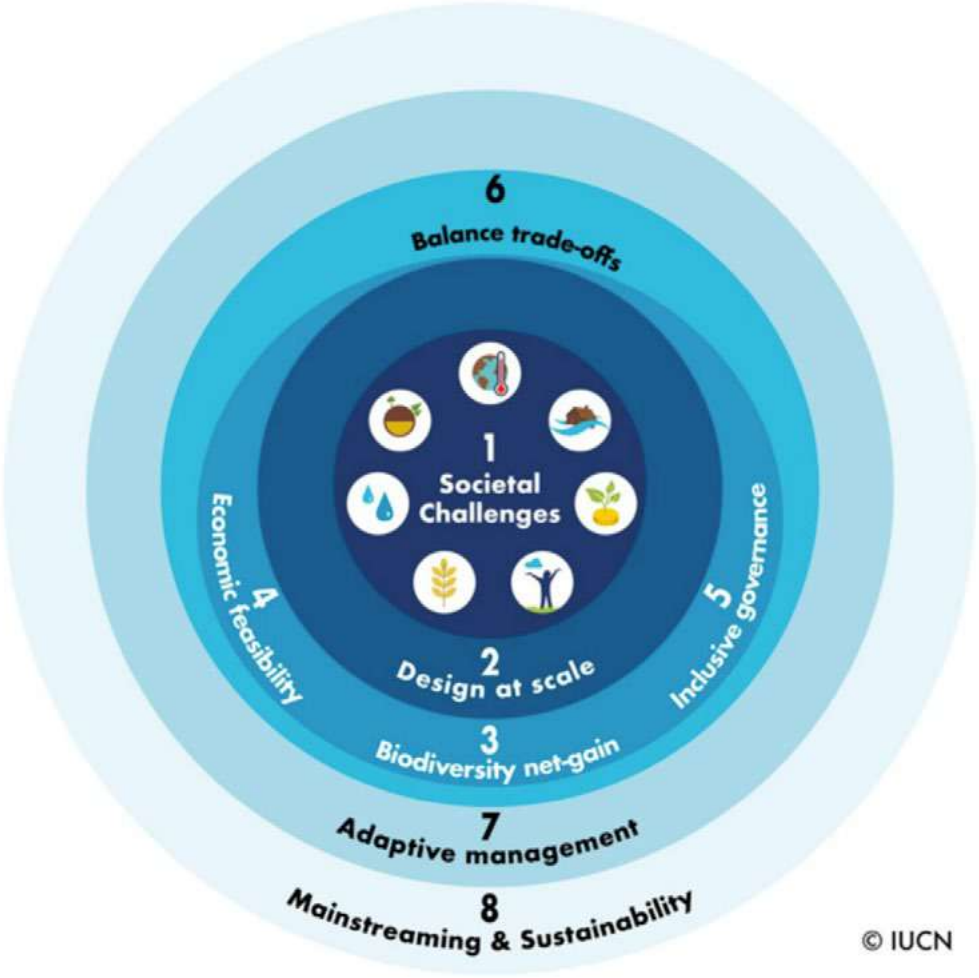


Figure 1.1 Relation across the Criteria of the IUCN Global Standard for NbS (IUCN, 2020)

In this respect, the IUCN Global Standard serves not only as a validation tool but also as a practical guide to improve the design, implementation, and scalability of NbS initiatives, fostering shared learning and helping practitioners align local interventions with broader sustainability and biodiversity objectives. Aligning NICE pilots with the IUCN Global Standard supports the design and implementation of innovative NbS approaches by highlighting essential components and expected outcomes. This alignment enhances the credibility and quality assurance of the solutions, facilitates replication and upscaling, and strengthens policy relevance by grounding NICE Urban Real Labs (URLs) in a framework widely recognized by governments, municipalities, and international organizations. Additionally, it promotes cross-learning across different NbS typologies and urban contexts, enabling cities to integrate NbS into broader resilience and sustainability strategies.

- Within this Deliverable, the alignment of the NICE URLs with the Global Standards is presented, guiding the considerations required by each NbS typology to effectively align with the eight criteria. The main objectives are:
- To review how the NICE Urban Real Labs relate to the eight criteria of the IUCN Global Standard.
- To extrapolate from the specific pilots to broader typologies and identify key considerations for design and implementation to ensure alignment with the Standard. This includes aligning with the societal challenges and the list of indicators outlined in the IUCN NbS Handbook.

1.2 Methodology

The alignment process combined a review of the IUCN Global Standard with inputs from partners responsible for the NICE Urban Real Labs (URLs). The process began with a review of the IUCN Global Standard for NbS, analyzing its criteria in the context of urban water management. Subsequently, all partners involved in the design and piloting of the NICE URLs were engaged to gather insights on how their respective URLs relate to each of the eight IUCN criteria. This information was synthesized into main findings for each of the URLs.

Based on the analysis of the NICE URLs and their alignment with the IUCN Global Standard, cross-cutting guidelines were developed describing how each of the eight criteria can be addressed by each NbS typology. For each typology, the most relevant criteria were identified, along with specific strengths and potential gaps. This step highlights where a given typology naturally aligns with the Standard and where additional attention may be required.

As part of the guideline development, the main societal challenges relevant to each NbS typology, derived from the EU NbS Handbook for practitioners, were identified in relation to Criterion 1: NbS effectively addresses societal challenges. In addition, drawing on the experience of the NICE URLs, the most pertinent indicators were selected for each typology with respect to Criterion 7: NbS are managed adaptively, based on evidence.

2.
GUIDELINES

Nature-based Solutions (NbS) are increasingly being applied for the management and treatment of various types of water. These technologies offer numerous advantages, including low construction and operational costs, minimal maintenance requirements, positive landscape integration, and environmental sustainability.

By mimicking the natural processes occurring in ecosystems, NbS combine physical, chemical, and biological mechanisms to remove pollutants, making them practical, resilient, and effective solutions for decentralized water and wastewater management.

Despite their growing recognition and widespread adoption, adequate technical knowledge for proper design, implementation, and operation is still often limited. The objective of this document is therefore to provide comprehensive guidance and to expand technical understanding for the implementation of innovative NbS within the framework of the NICE project.

These guidelines address key aspects to consider for the replication of these systems. Because different NbS are designed for different purposes, the level of knowledge required varies depending on the type of solution. To provide clarity, the NICE project guidelines have been structured into the following sections:

- **Introduction to the systems**
- **Required data before designing a project**
- **Design**
- **Design example**
- **Implementation**
- **Management, operation, and maintenance**

In addition to the technical guidelines, each system is accompanied by an **assessment** aligned with the International Union for Conservation of Nature Global Standard for Nature-based Solutions. This alignment ensures that the proposed solutions not only meet technical performance requirements but also comply with internationally recognized criteria related to environmental integrity, governance, stakeholder engagement, economic feasibility, and adaptive management. The detailed methodological framework for alignment with the IUCN Global Standard is presented in Section 2 of this Deliverable.

Furthermore, beyond the system-specific guidelines, a dedicated section is included addressing the **use of substrate materials and adsorbent media** in different Nature-based Solutions. This section provides technical recommendations for material selection, performance optimization, and pollutant removal enhancement.

2.1 Rain gardens for Stormwater treatment

Gdansk, Poland

2.1.1 Introduction
2.1.2 Required data before designing a project
2.1.3 Design
2.1.4 Design example
2.1.5 Implementation
2.1.6 Management, operation and maintenance
2.1.7 Alignment with the IUCN global standards
2.1.8 References



2.1.1 Introduction

Urbanization significantly alters the natural hydrological cycle, replacing permeable vegetated areas with impervious surfaces that increase the volume and velocity of stormwater runoff.

This process contributes to frequent urban flooding, pollution of surface waters, and degradation of urban biodiversity and ecosystem services. In response to these challenges, Nature-based Solutions (NbS) such as rain gardens offer multifunctional, cost-effective alternatives to conventional grey infrastructure.

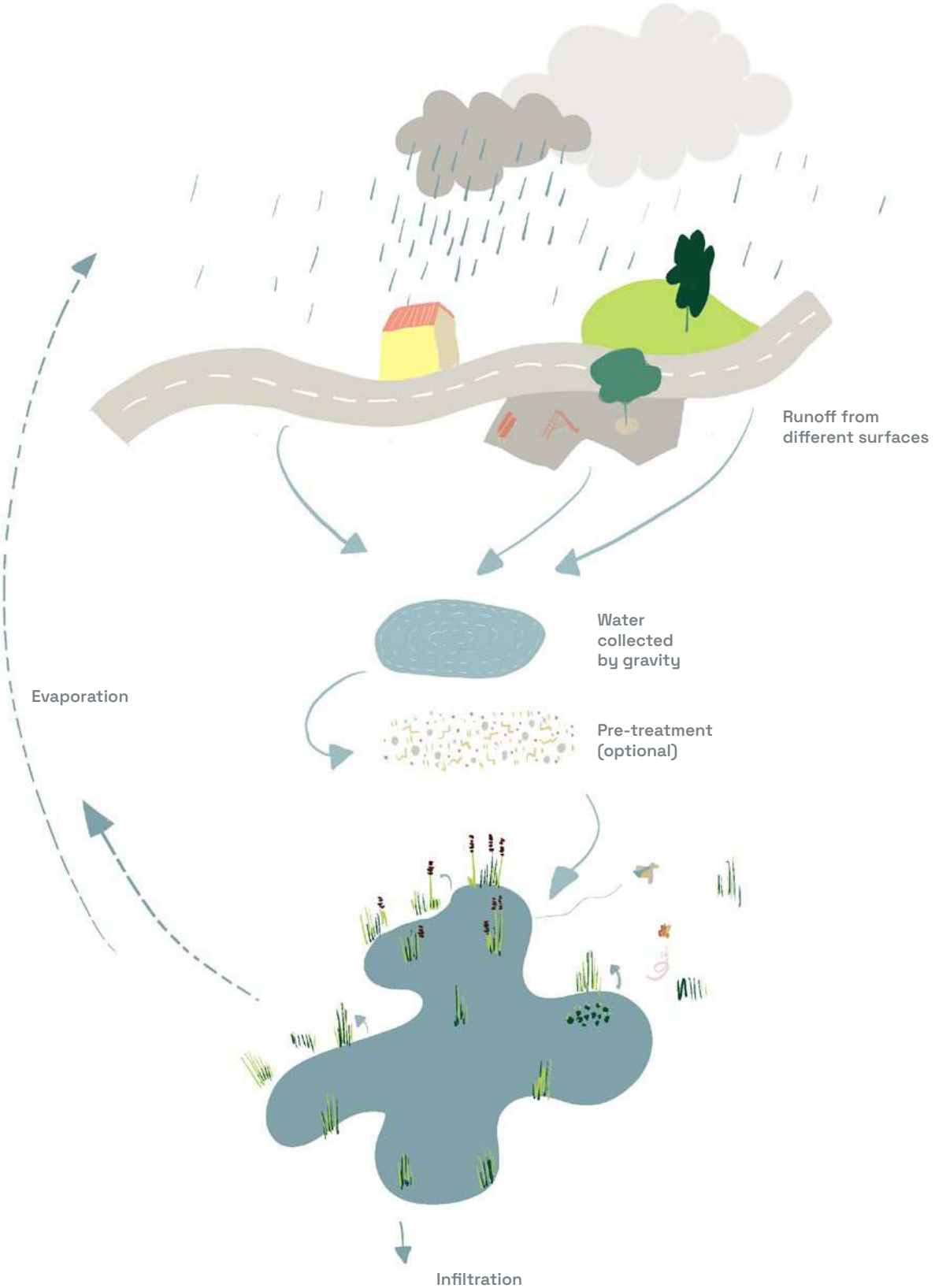
In these guidelines, rain gardens are treated not only as green infrastructure elements but as engineered stormwater treatment and retention systems designed according to clearly defined functional and hydraulic criteria. Rain gardens are NbS designed to capture, store, and filter stormwater runoff while delivering multiple co-benefits, including biodiversity enhancement and climate adaptation.

A rain garden (also known as a bioretention cell or vegetated swale) is a bioretention shallow basin designed to collect by gravity, detain, and retain stormwater runoff from adjacent impervious surfaces such as roofs, roads, and parking lots. Rain gardens provide temporary retention of stormwater conveyed by gravity, combined with pre-treatment, filtration, and controlled overflow mechanisms, depending on site-specific design and functional requirements. This water is subsequently taken up by vegetation, evaporated, and, to a lesser extent, infiltrates the soil after filtration. Consequently, rain gardens contribute to enhancing local biodiversity, improving the microclimate, and supporting the recharge of the aquifer. The Rain gardens combine engineered soil substrates, native or adapted vegetation, and optional underdrain systems to promote water retention, pollutant removal, and ecological enhancement. The plants in rain gardens must cope with dry and wet conditions.

These systems are classified as small-scale NbS for urban stormwater management and are particularly suitable for decentralized applications in public and private spaces. Within the context of the NICE, rain gardens are considered essential in closing urban water loops and mitigating the impacts of diffuse pollution and flash flooding, particularly in areas with limited space and high runoff coefficients.

Rain gardens provide multiple benefits that extend well beyond stormwater management:

Hydrological regulation	*detention and retention, which leads to total reduction of surface runoff volume and peak flow; promotion of groundwater recharge.*
Water quality improvement	*removal of sediments, nutrients (N, P), heavy metals, hydrocarbons, and pathogens.*
Biodiversity support	*creation of habitats for pollinators, birds, and other urban wildlife.*
Climate resilience	*mitigation of urban heat island effects and localized flood risks.*
Social and educational benefits	*enhancement of urban aesthetics, recreation, and community engagement in green infrastructure.*
Given their modular nature, rain gardens can be adapted to diverse contexts	*urban, peri-urban, or rural – and to different climatic zones, land-use typologies, and pollutant loads.*


Runoff from
different surfaces
Water
collected
by gravity
Pre-treatment
(optional)
Evaporation
Infiltration

2.1.2 Required data before designing a project

This section will specify the input data required to design a rain garden system. It concerns loads and concentrations of contaminants as well as flow data series. These data constitute mandatory inputs for all subsequent design steps and directly determine the sizing, configuration, and performance of the rain garden system. This section will also present the output data necessary to fix the design, including ponding depth, retention volume, and the concentrations targeted, as well as the volume of stormwater runoff to be managed.

Effective and site-specific design of rain gardens as NbS requires a comprehensive understanding of the environmental, hydrological, and infrastructural context. This section outlines the essential input data needed to support a robust design process and presents the expected output data required to determine system configuration, scale, and performance.

Input data before designing

A successful rain garden design must begin with the systematic collection of input data to assess feasibility, constraints, and potential functionality. These data can be grouped into several main categories: hydrology, soil, spatial conditions, water quality, climate, biodiversity, and legal framework.

HYDROLOGICAL and HYDRAULIC DATA

Rain gardens must be dimensioned based on expected stormwater inflows:

- *historical precipitation records and intensity, duration, and frequency data for the site, including design rainfall events and allowance for short-duration extreme precipitation*
- *runoff volumes and flow from catchment modelling*
- *soil infiltration capacity to determine the infiltration rate (e.g., mm/h)*
- *groundwater depth and soil layers to assess risks of submergence or contamination*



SPATIAL DATA and INFRASTRUCTURE

- *location, dimensions, and flow capacity of existing grey infrastructure, such as drainage sewers, combined sewer systems, and culverts*
- *conditions of adjacent surfaces (roads, sidewalks, etc.), including distinctions between permeable and impermeable areas, which directly influence runoff coefficients*
- *detailed mapping of underground utilities (potable water supply, wastewater system, gas mains, electrical and telecommunication cables)*
- *inventory of existing green and blue infrastructure (ponds, wetlands, vegetated swales, green roofs)*
- *spatial identification of zones suitable for additional retention and infiltration (e.g., underutilized green strips, tree pits, traffic islands)*
- *maps of the area, slope gradients, and available area for construction*

SOIL CHARACTERISTICS

- *infiltration rate, granulometric composition, organic matter content, and permeability - these parameters determine the efficiency of infiltration, filtration, and pollutant removal*

CLIMATE and FLOOD RISK DATA

- *regional trends in precipitation, evapotranspiration, and potential droughts (which may influence the garden's resilience)*
- *flood hazard maps and documentation of historical flood events*
- *urban topography and catchment delineation to identify areas with high runoff generation and flow accumulation*

BIODIVERSITY and ENVIRONMENTAL CONDITIONS

- *existing plant communities and faunal presence (particularly pollinators and amphibians)*
- *potential to increase native species diversity and create habitat linkages*
- *data on air quality (PM10; PM2.5, NOx),*
- *evaluation of existing ecosystem services in the pilot area, such as microclimate regulation, pollutant buffering, and recreational value*

WATER QUALITY and POLLUTION SOURCES

The design must consider the pollutants expected in the stormwater:

- *baseline concentrations of contaminants such as suspended solids (TSS), nutrients (total nitrogen - TN, total phosphorus TP), PAHs (Polycyclic Aromatic Hydrocarbons), heavy metals, pathogens, and contaminants of emerging concern (CECs, including PFAS - Per- and Polyfluoroalkyl Substances)*
- *identification of pollution hotspots: roadways, industrial zones, parking areas, or areas with pet waste*

LEGAL and POLICY FRAMEWORK

- *presence of heritage-protected buildings or archaeological areas*
- *compliance with national or EU legislation related to construction, water reuse, and biodiversity conservation (e.g., EU Water Framework Directive, IUCN Global Standard for NbS, local land-use regulations, and water management strategies)*

Output data for designing

- The analysis of input data should lead to the determination of the following design-critical parameters:
- target stormwater retention volume (e.g., m^3 per design storm), derived from design rainfall depth, contributing catchment area, and runoff coefficients defined for the site, typically based on the 10- or 15-year return period rainfall event
- design ponding depth, commonly in the range of 150–300 mm, allowing temporary surface storage while ensuring rapid infiltration
- surface area of the rain garden derived from flow and volume calculations, using appropriate runoff coefficients
- filter media depth and composition, selected to optimize both infiltration and pollutant removal
- pollutant load reduction targets, aligned with expected performance (eg., ≥80% removal of TSS, ≥70% for COD - Chemical Oxygen Demand)
- expected peak flow reduction, especially relevant for sites with frequent pluvial flood risks (quantified in m^3/s or % reduction relative to baseline)
- vegetation plan, ensuring plant species selection is suitable for water stress conditions and pollution tolerance (salinity)
- Where possible, designs should be validated or complemented with modelling tools (eg, NICER developed as a part of NICE project WP6, SCALGO Live, etc.).

Possible use of existing guidelines and tools

Where methodologies already exist, the design process should also refer to standardized best practices and guidance documents, such as, eg. : IUCN Global Standard for Nature-based Solutions, The SuDS Manual CIRIA, US EPA Green Infrastructure Design Strategies, ISO 14090:2019

2.1.3 Design

Fundamental design steps

The design of a rain garden must follow a systematic sequence of calculations and decisions based on site-specific data. The design steps presented below reflect the logical order of actions required for practical implementation and are directly applied in the design example described later in this chapter.

Rainfall data – select the design rainfall event (e.g., from national intensity–duration–frequency curves or country-specific formulas such as Bogdanowicz–Stachy in Poland).

Catchment area – determine the size of the contributing catchment and runoff coefficients (ψ) for different surfaces.

Runoff volume and peak flow – calculate using:

$$Q = q \times \psi \times F$$

where:

q = rainfall intensity,

ψ = runoff coefficient,

F = impervious area.

Required retention volume (Vreq) – based on maximum rainfall depth (hmax) and effective impervious area.

Filter surface (Af) – estimate filter area using simplified formulas such as:

$$Af = \frac{Cr \times Ac}{k}$$

where:

Cr = runoff coefficient,

Ac = catchment area,

k = infiltration efficiency (0.3–0.6 depending on soil).

Ponding depth – typically 150–300 mm, allowing temporary storage while ensuring infiltration.

Safety factors and bypass capacity – account for events beyond the design storm and provide overflow structures.

All calculations should be based on the input data defined in Chapter: Required data before designing a project.

Determining the filter's surface

The filter surface is directly related to the size of the catchment and the retention requirements. General rules include:

- Design for **80–90% of annual rainfall events**; extreme events should be safely bypassed.
- Check **annual hydraulic loading (HL) and suspended solids (SS)** loads to avoid clogging.
- Identify the **critical event** in terms of pollutant or sediment load and ensure the system meets removal targets.

Determining the filter's material

The filter media must support both hydraulic performance and pollutant removal. Recommended layers include:

- **Vegetation layer** – native or adapted plants tolerant of alternating wet and dry conditions.
- **Filter media layer** – typically a sand–loam mix, optionally amended with compost or sorbents for contaminants of emerging concern (CECs), such as mineral sorptive materials or biochar, depending on the expected pollutant profile and monitoring objectives. Depth: 50–80 cm
- **Transition layer** – fine gravel, preventing migration of filter media.
- **Drainage layer** – coarse gravel with perforated pipes for controlled outflow.

Designing an aeration system

Rain gardens are designed to operate under predominantly aerobic conditions, which support pollutant removal and plant health. Active aeration systems are not used; instead, oxygen exchange is ensured through passive hydraulic and structural solutions, including:

- the use of porous filter media with adequate infiltration capacity,
- integration of vegetation, whose root systems enhance soil aeration,
- drainage layers that facilitate water movement and prevent prolonged saturation.

In specific cases, passive features such as gravel zones or vertical perforated pipes may be included to improve natural air circulation and water drainage.

2.1.3 Design example

A practical design example of a rain garden implemented within the NICE project is presented below.

This design example strictly follows the design principles, hydraulic assumptions, and functional requirements described in the previous sections and serves as their direct practical implementation.

The primary objectives of the rain garden system are:

- temporary retention and attenuation of stormwater runoff,
- reduction of suspended solids and associated pollutants,
- protection of downstream drainage infrastructure,
- provision of a monitored, research-oriented NbS installation,
- enhancement of local biodiversity and microclimate.

The system is designed as a gravity-driven, multi-stage treatment and retention system, integrated into existing green space.



Figure 2.1.2

Design example of the rain garden system as implemented at the Urban Real Lab 9 site

Design rainfall event

The design rainfall depth was calculated using the Bogdanowicz–Stachy formula, as recommended for Polish conditions:

$$h_{max} = 1.42 \cdot t^{0.33} + \alpha \cdot (-\ln(p))^{0.584}$$

where:
hmax – maximum rainfall height [mm],
t – duration of the design rainfall [min],
p – exceedance probability, p □ [0;1],
α – scale parameter dependent on the region and the rainfall duration.

Assumptions used in the project

- rainfall duration: t=45 min
- exceedance probability: p=0.1
- regional scale parameter: $\alpha = 8.944 \cdot \ln(td) - 18.6$ for td = 30 to 60 min
- $\alpha = 8.944 \cdot \ln(45) - 18.6 = 15.447$

Calculated design rainfall depth

$h_{max} = 30.1$ mm ≈30 mm

This rainfall event was adopted as the design basis for retention sizing.

Catchment delineation and runoff coefficients

The rain garden receives stormwater and meltwater from the following contributing areas in Table 2.1.1.

Catchment	Area [ha]	Runoff coefficient ψ
Impervious driveway (f_1)	0.0390	0.90
Adjacent semi-permeable area (f_2)	0.0060	0.40
Sedimentation tank (f_st)	0.0017	1.00
Rain garden surface (f_rg)	0.0069	1.00

Table 2.1.1

Catchment areas and corresponding runoff coefficients used for rain garden design calculations

Vegetated lawn areas and embankments were excluded from the calculations. The system design is shown in Figure 2.1.1.



Figure 2.1.1

Plan of the system for purification and retention of surface runoff of rainwater.

1 Surface runoff inlet system
2 Hump
3 Lowered curb
4 Flow channel
5a 5b Sedimentation tanks
6 Wooden sheet pile wall
7 Filter
8a Upper bypass
8b Lower bypass
9 Rain garden



The system consists of a surface runoff inlet that directs stormwater into the treatment unit.

A hump and lowered curb regulate inflow and protect the system from excessive hydraulic load ❷❸. The flow channel ❹ conveys water to the two stage sedimentation tanks [❺a, ❺b], where coarse particles settle before entering the filtration segments. The wooden sheet-pile wall stabilizes the structure ❻, while the filter casing and filter wlower bypass structures allow excess water to be diverted during high-flow events, ensuring hydraulic safety [❽a, ❽b]. The treated water is finally discharged through the end cap into the rain garden area.

Calculation of peak inflow and sedimentation requirements

Maximum stormwater inflow volume:

$Q = q \cdot \psi \cdot F$

where:

q – rainfall intensity [dm^3 s-1 ha-1],

ψ – runoff coefficient [-],

F – impervious catchment area [ha].

The rainfall intensity was adopted according to the guidelines of Gdańskie Wody q = 174 dm^3 s-1 ha-1

Maximum stormwater inflow to the sedimentation tank QST:

QST = 174 dm^3 s-1 ha-1 · (1 · 0.0017 ha + 0.90 · 0.0390 ha)

QST = 6.40 dm^3s-1

Volume of stormwater during a 15-minute rainfall – maximum inflow to sedimentation tank Q15min:

Q15min = 6.40 dm^3s-1 · 900 s

Q15min = 5.76 m^3

Adopted sedimentation tank volume:

- VAC = 2.6 m^3 (active volume)
- VD = 1.3 m^3 (dead volume)
- VAC+D = 3.9 m^3

where:

VRG – volume of the rain garden,

VAC – active volume of the sedimentation tank,

VD – dead volume of the sedimentation tank.

The smaller dead volume of the sedimentation tank allows for more frequent water quality monitoring, as the tank reaches the necessary water level more quickly, enabling flow to the filtration segments. However, this also increases the risk of more frequent filter replacement due to clogging caused by reduced sedimentation time and increased solid particle inflow.

In case of excessive inflow to the tank, water will overflow via a hardened channel directly into the rain garden RG1 (see Figures 2.1. 3-2.1.5).

Determination of required retention volume

The required retention volume was calculated as:

$Vreq = (F_1 \cdot \psi + F_2 \cdot \psi + FST \cdot \psi + FRG \cdot \psi) \cdot hmax$

Vreq = (390 m^2 · 0.90 + 60 m^2 · 0.4 + 17 m^2 · 1.0 + 69 m^2 · 1.0) · 0.03 m

Vreq = 13.8 m^3

Adopted retention volume

- Rain garden basin 1: VRG1 = 4.7 m^3
- Rain garden basin 2: VRG2 = 6.7 m^3
- Total retention (basins + sedimentation): VΣRG + AC + D = 15.3 m^3

Condition VΣRG +AC ≥ Vreq , VΣRG +AC = 14.0 m^3 ≥ Vreq = 13.8 m^3



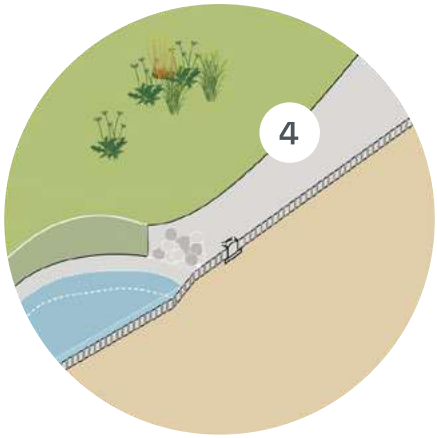


Figure 2.1.3

Longitudinal section through the runoff collection subsystem.

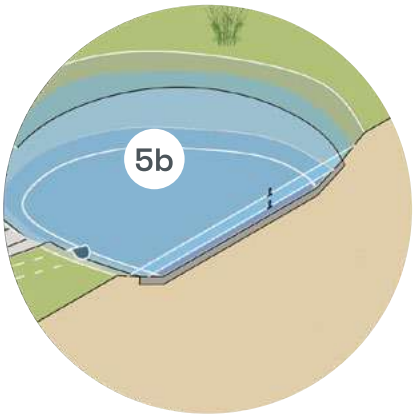




Figure 2.1.4

Cross-section through two sections of the sedimentation tanks (5a)-on top, (5b)-below.

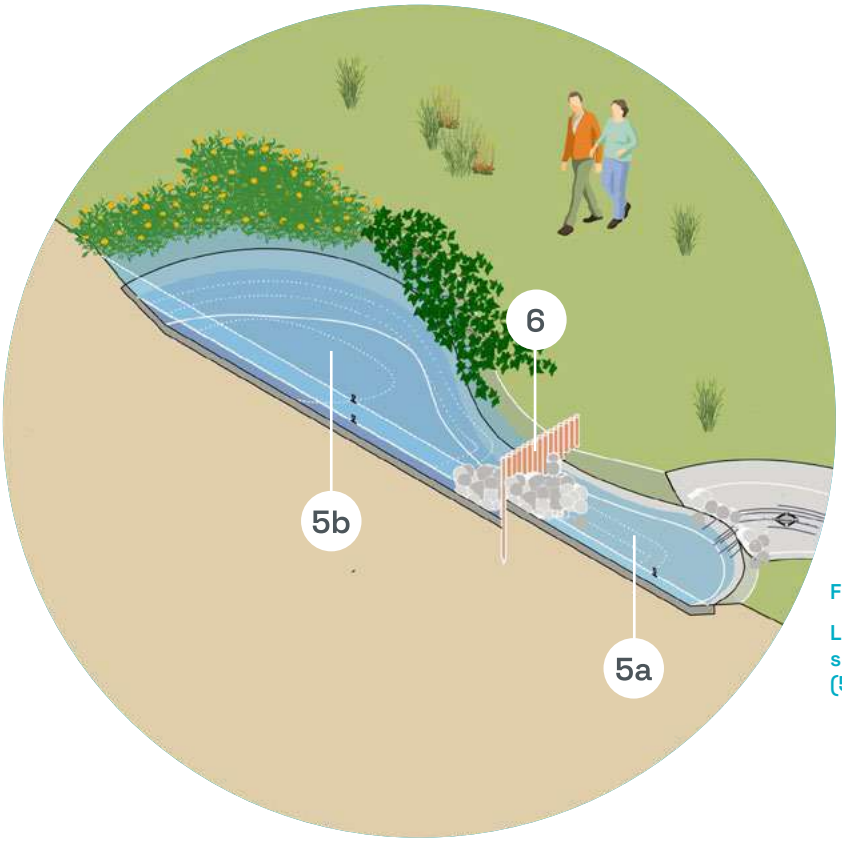


Figure 2.1.5

Longitudinal section through two sections of the sedimentation tanks (5a) and (5b).

Filter segments and hydraulic connection

The filtration system and subsequent rain garden are shown in Figures 2.1.6 and 2.1.7. Stormwater flows gravitationally through three filtration segments arranged in series, forming a multi-stage treatment system.

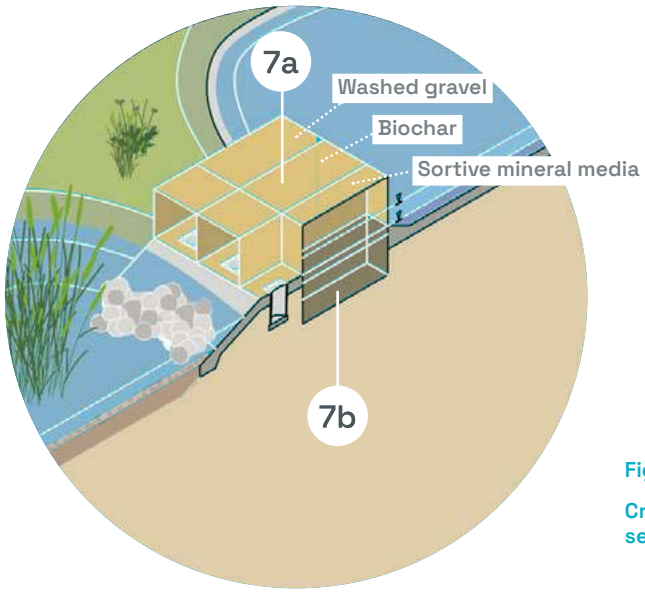


Figure 2.1.6

Cross-section through the filter segments (7)

Stormwater flows gravitationally through three filtration segments arranged in series:

- **washed gravel** (2–8 mm),
- **biochar** (2–8 mm),
- **sorptive mineral media** (provided by the contracting authority) - commercial material

This configuration enables sequential removal of pollutants, where the gravel layer provides initial filtration and hydraulic distribution, the biochar enhances adsorption of organic contaminants, and the mineral sorptive media supports further removal of nutrients and dissolved pollutants.

The segments are installed with a 2% longitudinal slope toward the rain garden basin. Sealed wooden partitions separate the segments and prevent mixing of filter materials while maintaining controlled hydraulic passage between stages. In the event of excessive inflow, emergency overflow from the sedimentation tank is conveyed via a hardened channel directly to the rain garden basin, protecting the filtration media from hydraulic overload and ensuring safe system operation during heavy rainfall events.

To support the selection of filtration media applied in the rain garden system, a comparative assessment of three granular sorptive materials was performed under identical hydraulic and experimental conditions. The evaluated media included washed gravel (2–8 mm), biochar (2–8 mm), and a mineral-based sorptive material. The comparison was based on filtration performance indicators derived from monitoring results, including pollutant removal efficiency and material behaviour under flow conditions (Figures 2.1.8 A-B).

An initial increase in nutrient and COD concentrations was observed at the early stage of operation for the biochar-based filter material, suggesting that a stabilization period following installation is needed.

Following this initial phase, the performance of the biochar stabilized, and the removal behaviour became comparable to that of the other filtration materials. In contrast, the remaining filter media exhibited occasional and less systematic concentration increases over time, indicating periodic release processes.

These observations highlight that filtration materials applied in rain garden systems may exhibit transient release phenomena under real operating conditions. Such effects should be considered in system design, start-up monitoring, and operational management, particularly during the early phase of filter operation and under variable hydraulic loading.

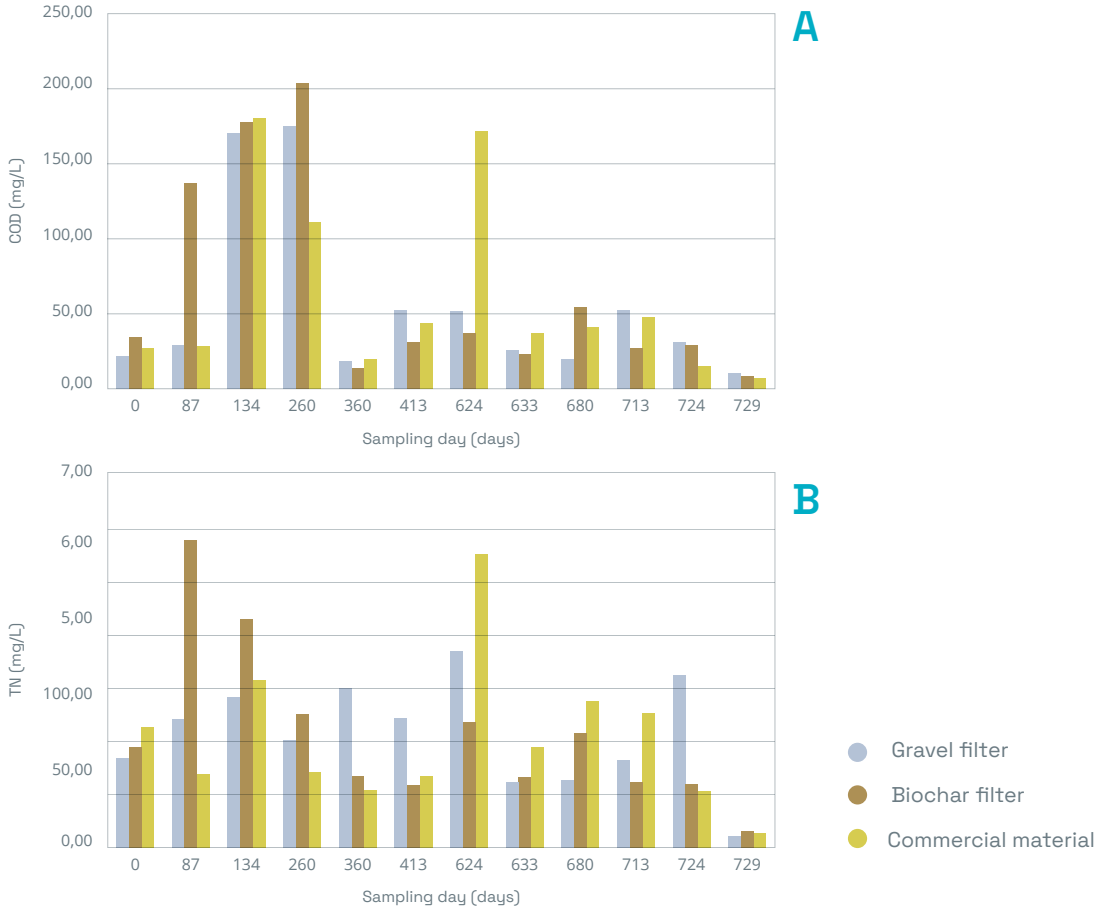


Figure 2.1.8

Comparison of COD (A) and TN (B) concentrations at the outlet of rain garden filtration segments filled with washed gravel, biochar, and commercial sorptive material over the monitoring period

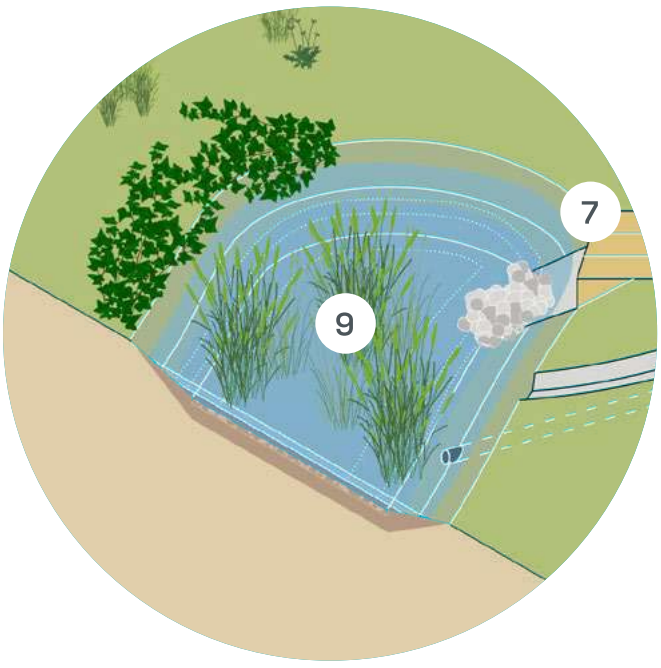


Figure 2.1.7

Longitudinal section through the filtration segments (7) and the retention basin planted with vegetation (rain garden - (9))

Rain garden basins and vegetation zone

The system consists of two shallow rain garden basins, separated by a low earthen embankment to allow staged retention.

Typical ponding depth does not exceed 0.40 m.

The basins support:

- evapotranspiration,
- sedimentation of residual solids,
- biological uptake by vegetation.

No deep infiltration into subsoil layers is induced; the system primarily functions through surface retention and controlled drainage.

Vegetation design – structure, zones and plant groups

The rain garden vegetation was designed as a multi-layered, zoned planting system, adapted to variable hydrological conditions and supporting both treatment efficiency and biodiversity.

In total, 15 plant species were used, comprising shrubs, perennials, ornamental grasses, ferns, and ground cover species, planted according to species-specific optimal planting densities to ensure proper establishment, hydraulic performance, and long-term vegetation stability.

Plant selection followed these principles:

- tolerance to periodic inundation and drying cycles,
- suitability for urban stormwater conditions,
- low maintenance requirements,
- support of pollinators and local biodiversity,
- resistance to frost and climate variability typical for Northern Europe.

Vegetation zones within the rain garden



Figure 9
Rain garden after implementation, showing functional and hydrological vegetation zones.

Zone 1 – Bottom of the rain garden basin (frequently inundated zone)

Hydrological conditions	• *temporary water ponding during rainfall events* • *longest retention time* • *high moisture availability.*
Functional role	• *evapotranspiration* • *nutrient uptake* • *stabilization of sediments* • *enhancement of biological treatment processes.*
Plant group	• *hydrophytes and moisture-loving perennials* • *approx. 7–8 species*
Examples	*Iris sibirica ('Pink Parfait') – Siberian iris* *Lythrum salicaria – Purple loosestrife* *Eupatorium cannabinum – Hemp agrimony* *Phalaris arundinacea – Reed canary grass* *Deschampsia caespitosa – Tufted hair grass* *Polygonum bistorta ('Superba') / Persicaria amplexicaulis – Bistort* *Matteuccia struthiopteris – Ostrich fern*



Zone 2 – Side slopes and intermediate zone (periodically wet–dry)

Hydrological conditions	• *short-term inundation* • *alternating wet and dry periods,* • *well-drained substrate.*
Functional role	• *slope stabilization,* • *interception of surface flow,* • *visual integration of the rain garden into surrounding green areas.*
Plant group	• *perennials and ornamental grasses tolerant to hydrological variability,* • *approx. 5–6 species*
Examples	*Echinacea purpurea – Purple coneflower* *Hemerocallis hybrida ('Winsome Lady') – Daylily* *Anemone × hybrida ('Margarete') – Japanese anemone* *Bergenia cordifolia ('Eroica') – Bergenia*



Zone 3 – Upper edge and surrounding area (rarely inundated zone)

Hydrological conditions	• *no regular ponding,* • *occasional splash or runoff contact.*
Functional role	• *structural framing of the system,* • *shading and microclimate regulation,* • *seasonal aesthetic value.*
Plant group	• *shrubs and ground cover species* • *number of species: approx. 3–4 species*
Examples	*Cornus alba ('Sibirica') – Red-twig dogwood* *Cornus sanguinea ('Midwinter Fire') – Dogwood* *Salix purpurea ('Nana') – Dwarf purple willow* *Hedera helix / Vinca minor – Ivy / Periwinkle (ground cover)*



2.1.5 Implementation

Implementation of a rain garden involves the following steps:

- **Site preparation** – clearing, excavation, and grading of the area.
- **Construction** – placement of filter layers, installation of drainage structures.
- **Planting** – selection and establishment of appropriate vegetation.
- **Commissioning** – initial inspection, water flow testing, and adjustments.

As-built documentation ensures conformity with design specifications.

2.1.6 Management, operation and maintenance

Proper operation and maintenance are essential to ensure long-term hydraulic performance, pollutant removal efficiency, and vegetation health of rain garden systems.

Main operational challenges

- Sediment clogging (colmatation): loss of infiltration capacity due to fine particles.
- Debris accumulation: leaves, litter, and trash are blocking inlets/outlets.
- Vegetation stress or mortality: caused by droughts, prolonged flooding, or poor species selection.
- Damage to subsurface infrastructure: blocked, collapsed, or corroded pipes.
- Long-term pollutant accumulation: metals, hydrocarbons, nutrients, PFAS, and other CECs retained in the filter media.

A summary of recommended routine operation and maintenance tasks, including inspection frequency and key observations, is provided in Table 2.1.3.

Task	Frequency	Notes
Inspect inlets, outlets, and pretreatment zones	Quarterly and after heavy rainfall	*Remove leaves, litter, or sediment blockages.*
Remove sediment from forebays/pretreatment chambers	1 time per year (spring or autumn)	*Prevent bypass and ensure treatment capacity.*
Check filter surface for standing water (>48 h)	After major storms	*Persistent ponding indicates clogging or drainage failure.*
Vegetation management (weeding, mowing, pruning, replacement)	2–3 times per growing season	*Use native or flood/ drought-tolerant plants.*
Remove invasive species	As required	*Maintain biodiversity and system resilience.*
Sediment removal from filter media	Every 2–3 years	*If infiltration declines; may require partial media replacement.*
Drainage pipe inspection	Every 2 years	*Manual or CCTV inspection; repair or replace as needed.*
Water quality monitoring (optional)	Once per year	*Track nutrients, hydrocarbons, depending on project scope.*

Table 2.1.3

Routine operation and maintenance tasks for rain gardens

Rain gardens should be periodically evaluated against key indicators:

- **Infiltration time:** Stormwater should infiltrate within 24–48 hours.
- **Vegetation cover:** Minimum 80% survival rate of planted vegetation after one year.
- **Sediment accumulation:** Not exceeding 5–10 cm in pretreatment zones before removal.
- **Pollutant removal efficiency:** (if monitored) reductions in suspended solids, nutrients, or metals.
- **Community engagement:** Evidence of involvement by residents or municipal services in upkeep.

2.1.7 Alignment with the IUCN global standards

This section will assess the alignment of this typology to the Nature-based Solutions (NbS) standard system from the International Union for Conservation of Nature and Natural Resources (IUCN).

Nature-based Solutions (NbS) implemented within the NICE project aim not only to provide effective technical performance but also to contribute to broader environmental, social, and governance objectives. The IUCN Global Standard for Nature-based Solutions provides an internationally recognized framework for designing, assessing, and scaling NbS, ensuring that such interventions deliver measurable societal benefits while maintaining ecosystem integrity and long-term sustainability.

This section evaluates how the presented NbS typology aligns with the eight criteria of the IUCN Global Standard. The assessment highlights key strengths, identifies potential gaps, and outlines considerations supporting effective implementation, adaptive management, and replicability of the solution in different urban contexts.

IUCN criterion	Status	Commentary	Actions to fulfil or strengthen alignment
C1. Address societal challenges	+	The rain garden addresses stormwater runoff pollution local flooding risk and lack of green space while providing recreational and educational benefits.	Strengthen explicit linkage to municipal flood risk management and climate adaptation strategies.
C2. Design informed by scale	±	The system is designed for a defined micro-catchment and demonstrates transferability but upscaling effects have not yet been quantified.	Apply the design methodology to multiple sites and assess cumulative retention and treatment capacity at the neighbourhood scale.
C3. Net gain to biodiversity	+	Introduction of a multi-layered vegetation system (~25 plant species) creates new urban habitats and supports pollinators.	Introduce systematic biodiversity monitoring (plant survival pollinator presence species richness).
C4. Economic viability	±	The system delivers multiple co-benefits but no formal life-cycle cost or ecosystem service valuation has been conducted.	Perform a capex/opex comparison with grey infrastructure and quantify avoided flood damage and treatment costs.
C5. Inclusive governance	+	Design and site selection involved students academic staff and university authorities ensuring transparency and acceptance.	Extend stakeholder engagement to residents and NGOS in future municipal implementations.
C6. Balance of trade-offs	+	Technical objectives (retention and treatment) were balanced with social and aesthetic functions of the site.	Document trade-offs and decision criteria to support replication in space-constrained urban areas.
C7. Adaptive management	±	Operation and maintenance tasks and monitoring points are defined but long-term performance data are still limited.	Establish a structured long-term monitoring programme with defined performance thresholds and response actions.
C8. Mainstreaming & sustainability	±	Knowledge transfer to the municipal water utility is ongoing but formal policy integration is not yet completed.	Integrate rain gardens into municipal stormwater standards design manuals and training programmes.

Table 2.1.4 Alignment of the rain garden system with the IUCN Global Standard for Nature-based Solutions

IUCN criterion	Considerations
C1. Address societal challenges	• *Define the primary water-related challenge being addressed (urban flooding, diffuse pollution, groundwater recharge, or heat stress).* • *Quantify runoff volumes, pollutant loads, and local drainage deficits to demonstrate relevance.* • *Integrate rain gardens into urban liveability goals, such as creating recreational or aesthetic green spaces.* • *Explicitly link the intervention to broader policy drivers, including climate adaptation plans and sustainable drainage strategies* • *Communicate multifunctional benefits, such as stormwater control, microclimate regulation, and community well-being.*
	Main societal challenges addressed by this typology:  GREEN SPACE MANAGEMENT | PARTICIPATORY PLANNING & GOVERNANCE | WATER MANAGEMENT | NATURAL & CLIMATE HAZARDS
C2. Design informed by scale	• *Size the system based on catchment characteristics, runoff coefficients, and rainfall intensity rather than aesthetic constraints alone.* • *Incorporate treatment trains, such as sedimentation and filtration, appropriate to the expected pollutant profiles.* • *Ensure hydraulic connectivity to surrounding drainage infrastructure, including safe overflow pathways.* • *Consider replication and interconnection of rain gardens to address the neighborhood or local scale, instead of enlargement of the solution.* • *Adapt engineered soil media, vegetation, and optional underdrains to local climate and soil characteristics and composition.*
C3. Net gain to biodiversity	• *Prioritize native or climate-adapted plant assemblages capable of tolerating alternating wet and dry conditions.* • *When possible, prioritize species diversity to create microhabitats for pollinators, birds, and soil organisms.* • *Avoid ornamental monocultures that limit ecological function.* • *Design soil profiles to support microbial processes critical to pollutant removal.* • *Establish biodiversity indicators (species presence, vegetation survival, habitat use) as part of monitoring.*
C4. Economic viability	• *Evaluate costs across the life cycle of the NbS, including avoided grey infrastructure expansion and reduced stormwater treatment loads.* • *Highlight co-benefits such as urban cooling, amenity value, and property enhancement.* • *Design for low maintenance and passive operation to minimize O&M costs.* • *Use modular, replicable construction methods to support scaling.* • *Compare lifecycle costs with conventional drainage solutions to demonstrate economic justification.*

Table 2.1.5 Key Considerations for the Alignment of Raingardens for Stormwater Management with the IUCN Global Standards

IUCN criterion	Considerations
C5. Inclusive governance	• *Use participatory processes to align technical design with community needs. Leverage the potential social and recreational benefits of rain gardens among diverse stakeholders* • *Provide clear communication on the function to avoid perception as purely decorative landscaping.* • *Encourage co-management models* • *Document decision-making to support transparency and replicability.*
C6. Balance of trade-offs	• *Balance hydraulic performance with usability of public space.* • *Ensure safety, accessibility, and visual integration into urban landscapes.* • *Address potential trade-offs such as land take, maintenance responsibilities, or seasonal variations in performance and aesthetic value.* • *Design multifunctionality intentionally; stormwater infrastructure should also serve social and ecological roles.* • *Clarify long-term ownership and maintenance obligations to avoid governance gaps.*
C7. Adaptive management	• *Establish monitoring schemes for the inflow and outflow quality, infiltration performance, and vegetation health.* • *Include inspection of sediment accumulation and filter media lifespan* • *Adjust plant composition or soil media if performance declines under real conditions.* • *Integrate rain gardens into urban environmental monitoring frameworks.* **Relevant indicators of NbS performance and impact to be considered for Stormwater Raingardens:** *Water management:* *3.2: Water quality: general urban* *3.3: Water quality: TSS content [mg/L]* *3.4: Nitrogen and phosphorus concentration or load [%]* *3.5: Metal concentration or load [%]* *3.6: Water quality: total faecal coliform bacteria content of NBS effluents [No.]* *4.1: Infiltration rate [%] or [mm/h]* *4.11: Rainfall storage capacity of NBS [mm/%]* *4.38: Water quality: basic physical parameters* **Evaluating the Impact of Nature-based Solutions: A Handbook for Practitioners (EC, 2021)*
C8. Mainstreaming & sustainability	• *Embed rain gardens within policies at the local level or climate adaptation strategies.* • *Develop technical guidance and design templates to support replication.* • *Facilitate knowledge transfer to practitioners, utilities, and planning authorities.* • *Align implementation with the policy landscape and regulatory frameworks (Water Resilience Strategy, Water Framework Directive).* • *Demonstrate how decentralized rain gardens contribute to local scale drainage systems and blue-green infrastructure networks.*

2.1.8 References

CIRIA, 2015
The SuDS manual (C753)

European Commission, 2000
Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy (Water Framework Directive)

European Commission, 2024
Nature-based solutions

International Union for Conservation of Nature, 2020
Global standard for nature-based solutions: A user-friendly framework for the verification, design and scaling up of NbS

Kasprzyk, M., Szpakowski, W., Poznańska, E., Boogaard, F. C., Bobkowska, K., & Gajewska, M., 2022
Technical solutions and benefits of introducing rain gardens – Gdańsk case study. Science of the Total Environment, 835, 155487

U.S. Environmental Protection Agency, 2022
What is green infrastructure?

2.2 Green wall for Greywater treatment

Torino, Italy

2.2.1 Introduction
2.2.2 Required data before designing a project
2.2.3 Design
2.2.4 Design example
2.2.5 Implementation
2.2.6 Management, operation and maintenance
2.2.7 Alignment with the IUCN global standards
2.2.8 References



2.2.1 Introduction

Green walls are vertical systems that provide vegetation cover to the external – and possibly internal – walls of buildings.

According to the structure used to support vegetation growth, green walls are generally classified in (Figure 2.2.1.):

- **Living walls:** vegetation is planted in containers attached to the wall or is rooted to a supporting structure (e.g., geotextile) attached to the wall.
- **Green facades:** vegetation is planted at the base of the wall and climbs either on a supporting structure (e.g., steel or plastic mesh) or directly on the wall itself.

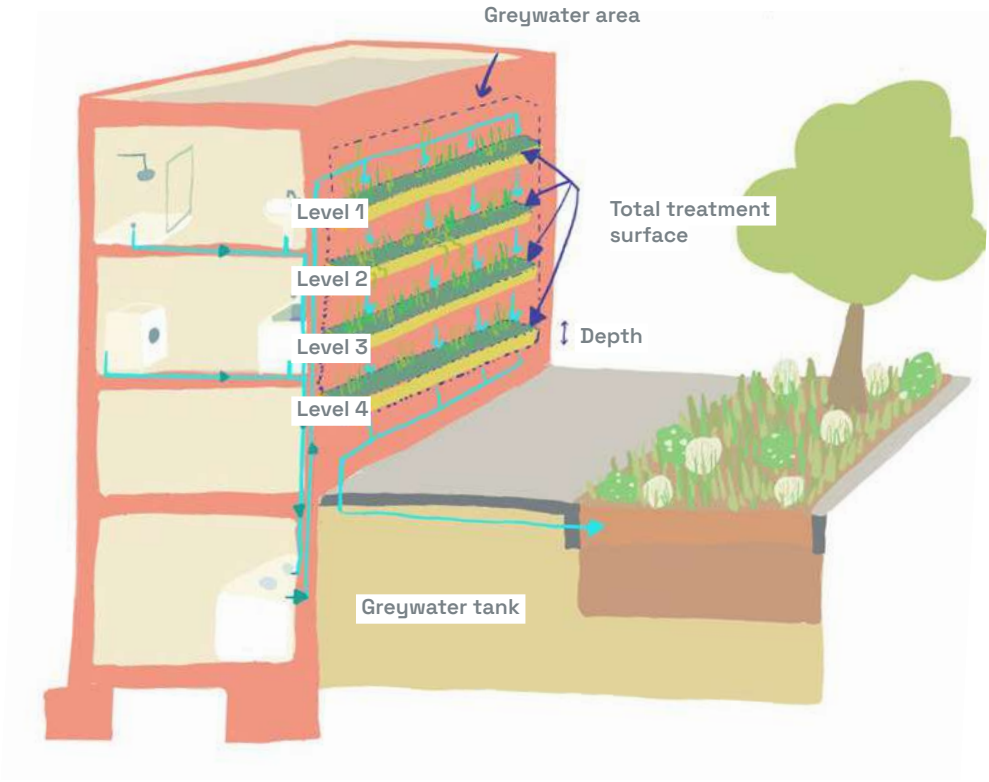
As part of the NICE project activities a living wall has been implemented, but the present guidelines also include green facades, considering that a review about the guidelines of both systems was delivered under NICE WP3.

These structures can provide many valuable ecosystem services. For example, they enhance thermal regulation and increase economic value of buildings, and they also favor biodiversity preservation and improve air quality at urban scale (Boano et al., 2020). However, the implementation of green walls must consider the water requirements, and therefore the use of greywater has been proposed as an alternative water source to mitigate the water footprint of green walls. Moreover, green walls can also be adapted to become greywater treatment systems, becoming NbS that generate reclaimed water resources for non-potable reuse.

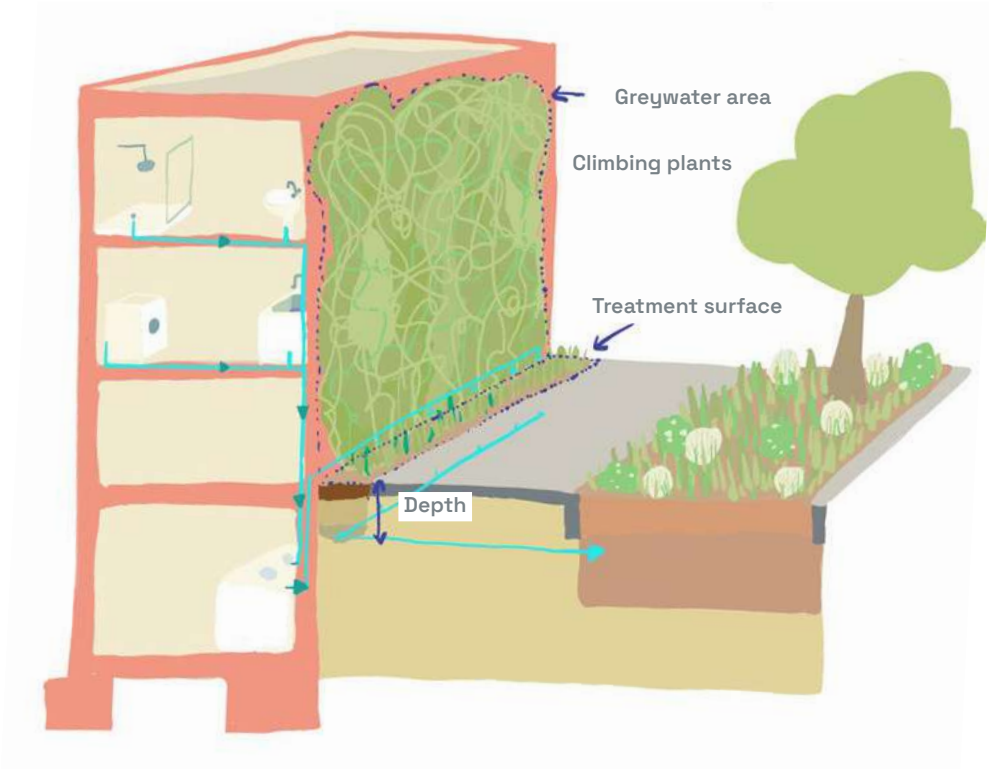
Figure 2.2.1

Schematization of key dimension parameters of green walls: on top, living walls left, on bottom green facades; .

LIVING WALLS



GREEN FAÇADES



Based on the literature review and considerations made within the NICE project, three design approaches and implementation schemes emerged, based on different hydraulic loading rates (HLRs) which were calculated using the surface area of the first level of pots (Figure 2.2.2.):

Firstly, green walls can be designed with a low HLR on the first level, up to 40 L m^{-2} d^{-1}, often lowering the HLR to a zero-discharge system, i.e., the example of the Total Value Wall™ studied by Lakho et al. (2021, 2022). Essentially, **a low HLR can be considered more related to a "direct" reuse of greywater to irrigate a green wall with a non-conventional water resource**, with the possibility of collecting and reusing small amounts of treated greywater that exceeds the irrigation demand of the green wall.

On the other side, green walls with **HLRs on the first level one order of magnitude higher** were tested, trying to maximize the volume of treated greywater per square meter of the green wall. In this case, **green walls are designed to produce a significant amount of non-conventional water resources**. This was the case for the Wall2Water design proposed in the NAWAMED project (Rizzo et al., 2023), built up from the experience of the SUPERGREEN project (Boano et al., 2021).

The third way lies in the middle, trying to maximize the multiple benefits of a green wall (multipurpose design), with HLRs on the first level ranging from 40 to 300 L m^{-2} d^{-1} (Pucher et al., 2022).

Indeed, if other ecosystem services are taken into consideration, the perspective on the different design approaches for green walls dealing with greywater may change (see Figure 2.2.2). For instance, if green wall surface coverage is considered an indicator of the aesthetic value, the Total Value Wall™ could be seen as the best option, as it maximizes the square meters of wall coverage with NbS per the cubic meters of unconventional greywater resource treated and available for irrigation.

Following this approach, the Wall2Water - that prioritizes treatment capacity - would offer a very low Total Value Wall™. If additional ecosystem services usually recognized for green walls were considered (e.g. heat island reduction, building insulation, noise control, biodiversity), it could become even more complicated to find the right balance, and dedicated multifunctional monitoring of green walls treating greywater should be developed, as for instance that proposed by Pucher et al. (2022). The future perspective will most likely confirm greywater as one of the most promising non-conventional water resources to unlock the potential of green walls in future cities, but a tailor-made design, considering the specific local needs in terms of ecosystem services would be needed, supported by solid monitoring data on multifunctionality of green walls according to different design approaches.

Figure 2.2.2

Overview of alternative design approaches for balancing the different ecosystem services proposed in literature: greywater treatment; wall surface coverage; other ecosystem services (e.g. heat island, insulation, noise, biodiversity).

	Greywater treatment (reuse)	Wall surface coverage (aesthetic)	Other ecosystem services (heat island, insulation, noise, biodiversity)
Total value wall™ Ghent, Belgium *Lakho et al. (2021, 2022)* 	● HLR first row 40 L m^{-2} d^{-1} Almost zero discharge, direct greywater reuse	●●●	? To be investigated, for instance by LCA (Lakho et al., 2022) or dedicated multipurpose monitoring campaign (Pucher et al, 2022)
Wien, Austria *Pucher et al. (2022)*	●● HLR first row 80-300 L m^{-2} d^{-1} Partly reuse of treated greywater	●●	
Wall2Water™ Farla, Italy *Rizzo et al. (2023)* 	●●● HLR first row > 300 L m^{-2} d^{-1} Direct greywater reuse	●	

2.2.2 Required data before designing a project

This section will specify the data and information that are needed to design a green wall.

TYPE of GREYWATER

*Greywater is divided into **dark** and **light** greywater, depending if wastewater from kitchen facilities is included or not. Moreover, the composition of greywater changes remarkably among countries and even within each country depending on different social, technological and climatic factors (Boano et al., 2020).*

Therefore, the identification of the type of greywater that can be collected can provide information on the expected range of concentrations of contaminants. If possible, it is thus advised to collect and analyze some samples of greywater for a better characterization of its composition.

GREYWATER-PRODUCING FACILITIES

*The amount of available greywater depends on the number of washroom sinks, showers, laundry machines, kitchen sinks and so on from which greywater will be collected. The **number and types of these facilities** should hence be identified, and the amount of greywater can then be either measured (if feasible) or estimated according to average production rates indicated in manuals.*

*The **location** of the facilities is also important to understand how to connect them to the piping system that conveys greywater to the green wall.*

WALL CHARACTERISTICS

*The **available vertical surface** of the wall will constrain the size of the green wall.*

*The **level of sun exposure** is also important for the choice of the plants.*

2.2.3 Design

As said in the introduction, living walls can be designed for greywater management with two distinct objectives: to a "direct" reuse of greywater, i.e. to irrigate a green wall with a non-conventional water resource and to produce and reduce a significant amount of non-conventional water resource by treating it.

Determining the filter's material

The filter media used in green wall pots (also called growing media or substrate) is a critical component that supports both plant growth and, in the case of greywater treatment, filtration and biological activity. Its composition depends on the specific function of the green wall (e.g., ornamental vs. treatment), but in treatment-oriented systems, the media must balance hydraulic performance, retention time, and microbial support.

Design guidelines for living walls for "direct reuse" of greywater

Greywater can be directly reused for irrigation of green walls without specific requirements of the filter's material. Hence, common growing media employed for green walls can be adopted.

Design guidelines for living walls for treating and reuse of greywater

In living walls for greywater treatment and reuse, typical filter's materials are composed of a mixture of equal volumes of an organic material (e.g., coconut coir) with lower permeability and a lightweight high-permeability material (e.g., expanded clay or perlite). The organic component is aimed at retaining moisture and nutrients and supporting microbial growth, while the lightweight material improves aeration and drainage. The two components should be mixed to ensure homogeneity of the overall filter's material.

Even though available literature does not provide clear evidence on preferred media type and/or additives (Boano et al. 2021, Costamagna et al., 2023, Sami et al. 2023) once a proper balance between high- and low-permeability media is achieved (Masi et al., 2016), the inclusion of specific additives (e.g., biochar) can improve nutrient retention and support microbial colonization of the filter media. Biochar can also significantly favor the removal of Contaminants of Emerging Concerns (e.g., pharmaceutical residuals – see section about adsorbent materials and substrates for NbS).

Determining the filter's surface

Design guidelines for living walls for "direct reuse" of greywater

Design guidelines for direct reuse of greywater concern the following parameters:

- **Depth and number of levels:** typical values of depth of the growing medium range between 15 to 60 cm (see Table 4). In relation to the number of levels, expect some specific experiments with a single level (e.g. Prodanovic et al., 2020), the number of levels range from 3 (e.g. Boano et al. 2021) to 10 (e.g. Pucher et al., 2022), up to the 15 used with felt modules by the Total Value Wall™ (Lakho et al. 2021). The depth should be chosen within this range (15 to 60 cm) based on the vertical size of the pots or modules, and the minimum number of levels. As a conservative assumption, we suggest > 15 cm per levels for minimum 3 levels, in order to reach a total treatment depth of a minimum 45 cm, being closer to the range of bed depth used in treatment wetlands (70-100 cm).

- **HLR on the total surface:** hydraulic loading rates all over the available treatments surface (i.e., considering the surface of all the levels , see Figure 1.2.1.) can be a useful parameter when the target is a direct reuse of greywater for the irrigation of a living wall; the suggested design value is < 20 L m^{-2} d^{-1}, lower than statistical range from literature (first quartile 30 L m^{-2} d^{-1}) and in between the HLR tested by Lakho et al. (2021) for the Total Value Wall™ (about 40 L m^{-2} d^{-1}) and typical irrigation demand in temperate climate (5 L m^{-2} d^{-1}, i.e. 5 mm d^{-1}); in any case, a detailed analysis on water demand by evapotranspiration is suggested during the detailed design when the prior target is the irrigation with greywater, based on climatic conditions, wall orientation, and selected plant species.

- **BOD_5 removal and outlet BOD_5 concentration:** if the design guidelines proposed here are used, an effective removal of BOD_5 (> 90%) and the compliance with strict law requirement for BOD_5 effluent concentration (< 10 mg L-1) would be expected (see Table 2.2.1.).

Design guidelines for living walls for treating and reuse of greywater

Design guidelines for living walls treating and reusing greywater related to the first surface (total area of the first levels) are based on the amount of greywater to be treated. The flow directly influences the first treatment surface area and, thus, the entire geometry of the green wall. The main parameters are listed below:

- **Depth and number of levels:** these parameters have the same standards of the green wall for "direct reuse" of greywater mentioned in the previous paragraph.

- **Hydraulic Loading Rate (HLR) on the first level:** hydraulic loading rate on the first level of a living wall treating greywater is suggested as a design parameter to check possible risk of clogging in long terms, when the implementation scheme primarily targets the treatment and reuse. Despite stress tests on NICE pilots have shown a promising resilience without evidence on short-term clogging with extremely high HLR on the first level (870 – 1300 L m^{-2} d^{-1}), other

authors tested more prudent values (100 – 300 L m^{-2} d^{-1} from the literature analyses) closer to design indication for treatment wetlands (< 160 L m^{-2} d^{-1} for unsaturated subsurface vertical flow wetlands filled with coarse sand 0.2 – 2.0 mm and treating greywater – Nivala et al., 2018). Therefore, a conservative threshold of < 300 L m^{-2} d^{-1} is suggested for full scale design, until more evidence emerges about the absence of clogging with higher HLR in the long term, as suggested by Pucher et al. (2022).

- **Organic Loading Rate (OLR) on the first level:** organic loading rate on the first level is another important design parameter to check possible risk of clogging in long terms, with an implementation scheme primarily targeting treatment and reuse; NICE pilots tested slightly higher (70 – 180 gCOD m^{-2} d^{-1}) OLR on the first level in comparison to other authors (40 – 130 gCOD m^{-2} d^{-1} from the literature analysis), but both ranges significantly exceed clogging limit usually suggested for treatment wetlands (< 20 gCOD m^{-2} d^{-1} for unsaturated subsurface vertical flow wetlands filled with coarse sand 0.2 – 2.0 mm – Nivala et al., 2018). Since the design thresholds of OLR for treatment wetland can be considered an empirical indication for avoiding at least bioclogging (i.e. the clogging due to biofilm development for biological treatment of wastewater – Pucher et al. 2019), a conservative value of < 40 gCOD m^{-2} d^{-1} is suggested; it must be noted that this value is quite conservative considering the literature review on living walls (lowest quartile from the statistical analysis), but still twice the value used for treatment wetland design.

- **Oxygen Consumption Rate (OCR):** in analogy with design methods for treatment wetlands, oxygen consumption rate can be assumed as a design parameter for living walls aiming to treat greywater by recreating the conditions of vertical subsurface flow treatment wetlands, i.e. vertical flowing from levels and batch-fed (Dotro et al., 2017); OCR is intended over the whole available treatment surface (i.e., considering all levels, see Figure 1) and the suggested minimum value of OCR is 20 gO_2 m^{-2} d^{-1}; the value is line with the statistical analyses of literature (18 – 40 gO_2 m^{-2} d^{-1}) and mainly based on detailed results from the NICE pilots (10 – 20 gO_2 m^{-2} d^{-1}); the value is also sufficiently conservative in comparison to the typical design value for vertical subsurface flow treatment wetlands (30 gO_2 m^{-2} d^{-1}, Dotro et al., 2017).

- **Hydraulic Retention Time:** additionally, living walls can also be designed to treat greywater by recreating the conditions of horizontal subsurface flow treatment wetlands, i.e., horizontally flowing from levels and continuously fed (Dotro et al., 2017). In this case, in analogy with design methods for treatment wetlands, hydraulic retention time can be assumed as a design parameter; we propose a minimum HRT > 1 day, according to literature revision (1 – 1.9 days); usually HF wetlands are never designed with HRT lower than a day, even considering the treatment of light greywater, but typical kinetic equations for HF (see Dotro et al. 2017) could also be useful for designing living walls using a horizontal flow approach.

- **BOD_5 removal and outlet BOD_5 concentration:** these parameters have the same standards of the green wall for “direct reuse” of greywater mentioned in the previous paragraph.

Parameter	Unit	Literature rev. Q1–Q3*	NICE stress tests**	Design indications		Treatment wetland guidelines***
				DIRECT REUSE	TREATMENT AND REUSE	
depth per level (from 1 to 15 levels)	cm	15–25	23	**>15 cm >3 levels**	**>15 cm >3 levels**	70–100
medium weight	kg m^{-2}	14.8–55.9	9			
HLR first level	L m^{-2} d^{-1}	100–300	871–1335 (Q1–Q3)	**N/A**	**<300**	<160 (VF sand 0.2–2.0 greywater)
OLR first level	gCOD m^{-2} d^{-1}	40–127	72.9–177 (Q1–Q3)	**N/A**	**<40**	<20 (VF sand 0.2–2.0)
HLR total	L m^{-2} d^{-1}	30–99	155–445	**<20**	**N/A**	
OCR	gO_2 m^{-2} d^{-1}	18–40****	10–20***** (Q1–Q3)	**N/A**	**>20 (if VF)**	30 (VF sand 0.2–2.0)
HRT	d	1.0–1.9	N/A	**N/A**	**>1 (if HF)**	To be verified with kinetic equations
BOD_5 removal	%	85–97	>90%	**>90**	**>90**	
BOD_5 conc. out	mg L^{-1}	2.1–8.9	0.5–7.6	**<10**	**<10**	

Table 2.2.1 Reference design values for green walls for greywater reuse.

VF: vertical subsurface flow wetlands;

HF: horizontal subsurface flow wetlands;

** Data from Deliverable 3.3 (Table 1.2.1, considering only living walls);*

*** Data from Deliverable 3.2;*

**** Dotro et al. (2017); DWA 2017 (Nivala et al., 2018);*

***** Calculated with COD;*

****** Calculated with BOD_5*

Designing system

Other elements that should be considered are:

Pre-treatment

Beside reducing the risk of clogging of the filter's material, the presence of a degreaser may act as a buffer to reduce the concentration of undesired components that could potentially damage plants of the green wall and/or biofilm within the filter's material. Following the indications from the stress tests with aggressive detergents run on the NICE's pilots, a degreaser with a minimum volume > 50 liters per person equivalent is suggested as primary treatment.

Feeding system

Although pressure-compensating drippers ensure a constant flow rate, they are particularly susceptible to clogging by suspended solids. In addition, they require a minimum operating pressure, which can represent a limitation in gravity-fed systems. Owing to the high risk of clogging, pressure-compensating drippers should therefore be used only with highly diluted greywater streams. As an alternative, perforated pipes can be employed, as they are generally less prone to clogging.

Post-treatment

Even though green walls typically reduce the concentrations of potential pathogens by 2-4 orders of magnitude, local regulations may require extremely low concentration of pathogens in reclaimed greywater. Depending on the type of reuse, the inclusion of a disinfection step (e.g., by a UV lamp) is advised to avoid health risks if the reuse entails the possibility of human contact with treated greywater (e.g., through aerosols generated by toilet flushing with reclaimed water).

2.2.4 Design Example

This chapter presents a practical example of how to apply the design principles introduced in the previous sections, using the case study of Cecchi Point in Turin, Italy, the NICE URL green wall pilot.

The methodology adapts dimensioning criteria from vertical subsurface flow treatment wetlands, tailored to the geometry and operational characteristics of living green walls. Specifically, this design approach is based on:

- the Hydraulic Loading Rate (HLR) [$L/m^2/day$],
- the Oxygen Transfer Rate (OTR) [$gO_2/m^2/day$].

These parameters are derived from literature on NbS and validated through the NICE project's experimental pilots. The Cecchi Point case serves as a replicable and validated example of living green wall application for greywater treatment and non-potable reuse in dense urban areas.

The living green wall installed at Cecchi Point, a cultural hub in Turin, was designed to treat 150 L/day of light greywater, primarily from hand basins (Table 2.2.2). The treated water will potentially be reused on-site for irrigating adjacent green areas. The system utilizes stacked modular units filled with engineered filling media to simultaneously support vegetation and microbial treatment activity. Cecchi Point Green Wall includes a primary pre-treatment through a grease trap, installed upstream to remove oils and solids and protect the filtration media from clogging.

Parameter	Value	Unit
Daily inflow (Q)	150	L/day
BOD_5	50	mg/L
COD/BOD ratio	2	—
Assumed temperature for sizing	6	°C
Potential end-use of treated water	Irrigation	—

Table 2.2.2

Cecchi point's greywater characteristics.

The treatment area is calculated using the recommended HLR, based on values validated in the literature for vertical subsurface flow treatment wetlands and living green walls.

Treatment surface_first level = Q / HLR = 150 L/day ÷ 250 L/m^2/day = 0.6 m^2

This value corresponds to the required treatment surface of the first level, where the primary pollutant load is applied, to avoid clogging phenomena.

Additionally, the OLR was calculated to verify that the first level of the living green wall, which receives the full greywater inflow, is not exposed to excessive organic stress. This is particularly important because the first level acts as the initial filtration and biological treatment layer, where most of the suspended solids and biodegradable organic matter accumulate. If the organic load exceeds the media's degradation and infiltration capacity, it can lead to clogging, anaerobic conditions, and reduced treatment efficiency. Based on literature and project benchmarks, an OLR threshold of 40 gCOD/m^2/day is considered the upper limit for sustainable operation. Ensuring the OLR remains below this value is essential to maintain the permeability and long-term functionality of the wall.

The calculated OLR is given by the formula:

OLR = Q × COD/Treatment surface_first level = 150 L/day × 0.100 g COD/L / 0.6 m^2 = 25 gCOD/m^2/day

This value is well below the recommended threshold of 40 gCOD/m^2/day for the first treatment level, ensuring that the system operates within safe hydraulic and biological limits and minimizing the risk of clogging.

The selected module (*Modulogreen*®; Figure2.2.3) contains 4 pots per level. The average size of each pot is 17 cm in length, 11 cm in width, and 12 cm in filling depth, with a treatment surface area of 0.01955 m^2 per pot. The modules are arranged in units with 3 vertical levels (i.e., 12 pots per unit).

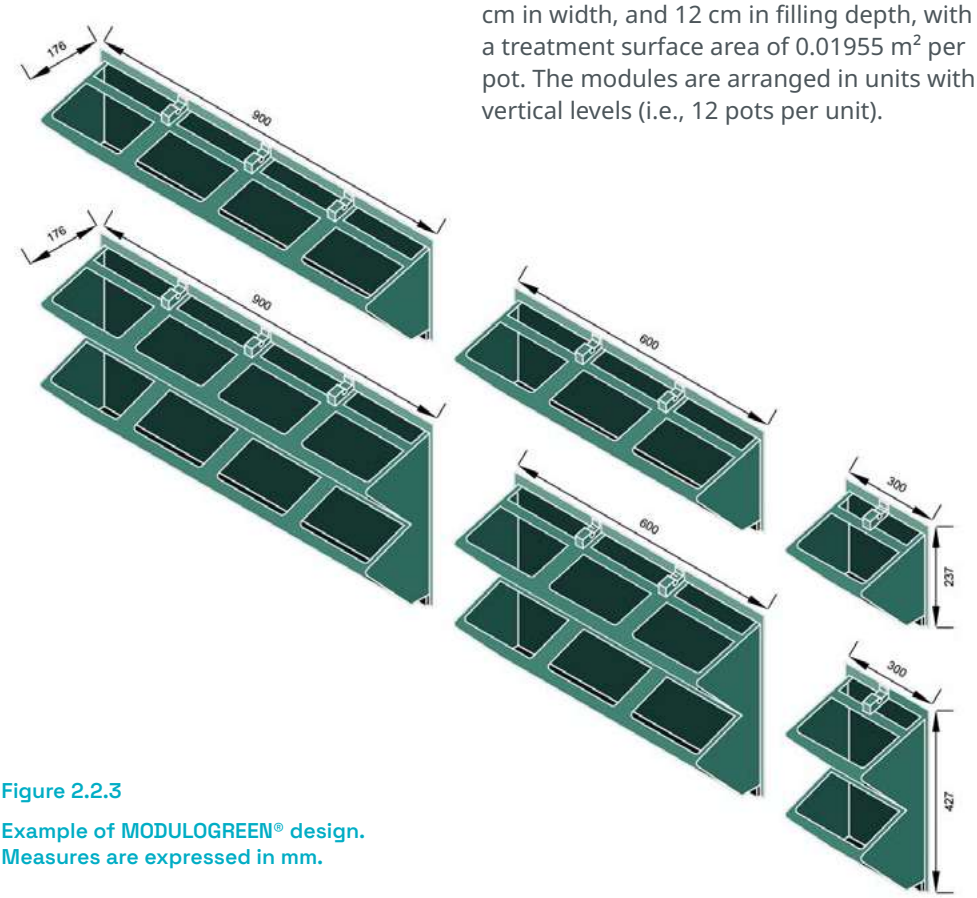


Figure 2.2.3

Example of MODULOGREEN® design. Measures are expressed in mm.

To ensure aerobic treatment conditions are met, we verify that the oxygen input (OI) exceeds the oxygen demand (OD). The latter is estimated as:

$OD = (Q \times BOD_5) / 1000 = (150\ L/day \times 50\ mgO_2/L) / 1000 = 7.5\ gO_2/day$

Given the design choice to use Modulogreen® with 3 levels per unit, the total treatment surface available for oxygen transfer is equal to $0.6\ m^2 \times 3 = 1.8\ m^2$. Assuming an OCR of $20\ g\ O_2/m^2/day$:

$OI = OCR \times \text{Total treatment surface} = 20\ gO_2/m^2/day \times 1.8\ m^2 = 36\ gO_2/day$

Since OI > OD, the system is expected to ensure aerobic conditions for effective water treatment.

The total number of planting pots required on the first level is determined by dividing the treatment surface by the area occupied by a single pot:

$n_pots = 0.6\ m^2 / 0.01955\ m^2/pot \approx 31$ pots (which was approximated to 32 pots based on design considerations and to maintain a conservative safety margin in the treatment capacity)

This ensures that the required hydraulic and organic loading is distributed across sufficient planting surface to meet design criteria.

Each Modulogreen includes 4 pots on the first level. Therefore, the number of modules required to achieve 32 pots in the first treatment level is:

$n_modules = 32 / 4 = 8$ modules

The 8 required modules have been installed in two parallel vertical columns, as illustrated in Figure 2.2.4, to align with the available architectural space, while ensuring both balanced water distribution and aesthetically integrated design. The arrangement also supports easy maintenance access and efficient use of vertical surface area, providing optimal performance without compromising the visual identity of the building envelope.

Each unit occupies approximately 0.6 m^2 of vertical wall space (net area). The total net surface of the wall is:

Net green wall area = 8 × 0.6 = 4.8 m^2

To account for spacing, framing, piping, and support structures, a transformation coefficient (Ct = 1.2) is applied:

Gross green wall area = Net green wall area × Ct = 4.8 × 1.2 = 5.76 m^2

This distinction is important for façade planning and integration into building design.

To summarise, the Cecchi Point living wall is dimensioned using validated vertical subsurface flow treatment wetland criteria, adapted to vertical modular systems.

The outcome can be summarised as follows:

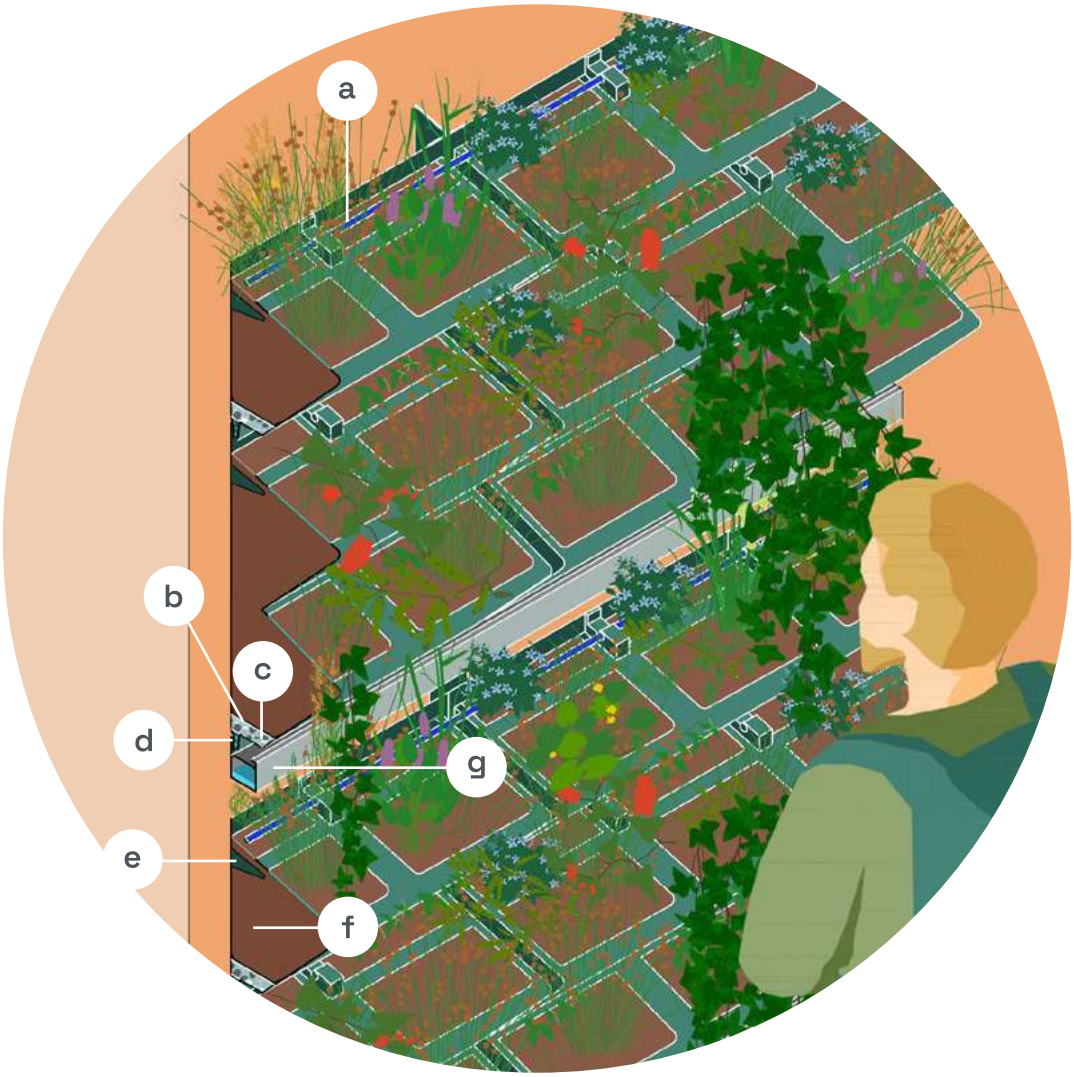
Treatment capacity: 150 L/day
Required treatment surface (first level): 0.6 m^2
Total pots: 96 (32 on the first level)
Modules: Modulogreen
Units: 8 (3 treatment levels, 4 pots per level)
Net GW area: 4.8 m^2
Gross GW area: 5.76 m^2 (Ct = 1.2)

This example represents a best-practice benchmark for replicating living greenwall systems for urban greywater treatment and reuse under the NICE project framework.



Figure 2.2.4

Cecchi Point living wall represenation (up) and installation photo (left), taken in June 2025.



- a Perforated pipe
- b Filter layers
- c Drainage layer
- d Excess water evacuation
- e Internal water distribution
- f Growing medium
- g Gutter for excess water recovery

2.2.5 Implementation

This section will present construction issues differentiating what is common to all green walls (refer to standardized guidelines) and what is specific to the systems discussed in these guidelines. On one hand, green walls for direct reuse of greywater, the structure of the system is expected to be quite similar to the one of a traditional green wall. On the other hand, living walls for treatment and reuse of greywater are characterised by different environmental conditions that require specific attention.

The most relevant differences are summarised in the list below:

- **Vegetation type:** a major difference compared to traditional green walls is that the plants used in living walls for treatment and reuse of greywater can be subject to high values of soil moisture. Therefore, robust plant species that tolerate periods of high humidity should be chosen for this type of application. However, it should be noticed that after an irrigation flush soil moisture is expected to decrease even in living walls for treatment and reuse of greywater, and periods of low soil moisture can be expected if the amount of supplied greywater decreases (e.g., during holidays if the number of building occupants decreases).
- **Degreaser unit:** greywater collected from the building wall is first conveyed in a degreaser tank to remove the possible oils and grease to avoid increasing hydrophobicity of the filter medium. The tank also serves to intercept coarse particulate material (e.g. hair) that may clog the irrigation system. The degreaser unit is typically built as a subsurface tank close to the green wall.
- **Irrigation system:** the use of drippers is discouraged because greywater increases the chance of clogging due to biofilm growth and straining of occasional fine particles that are not removed by the degreaser unit. It is hence recommended to use perforated pipes to avoid this risk.
- **Collection of treated greywater:** living walls for treatment and reuse of greywater lead to the production of reclaimed greywater that can be collected using a gutter at the bottom of each independent set of pots or modules, as in Figure 1.2.4. Depending on the envisioned reuse of greywater (e.g., if treated greywater is employed for irrigation of edible vegetation) and on local regulation, the inclusion of a UV lamp in the reuse circuit should be considered to ensure the absence of potential pathogens in water to be reused.

2.2.6 Management, operation and maintenance

Even though employing greywater in green walls increases the overall complexity of the system compared to irrigation with tap water, the challenges related to greywater use can be managed quite easily by implementing a few specific actions.

Main operational challenges

- **Clogging:** the irrigation system is slightly more subject to clogging, hence reducing the amount of supplied greywater. This risk is minimised by using perforated pipes for irrigation (see "Implementation").
- **Greywater dripping:** if the infiltration rate is lower than the average irrigation flow rate, greywater can pond on the surface of the filter medium and drip down from the wall, leading to undesired exposure of people to greywater. Proper choice of filter medium is crucial to avoid this risk (see "Design").
- **Distress and death of plants:** even though greywater is not harmful for vegetation, all green walls are foreseen to occasionally exhibit discoloration of leaves or even death due to disease or adverse environmental conditions. The deployment of multiple plant species - chosen according to local climate and sunlight exposure - is advised to decrease the number of plants that may experience stress at the same time.
- **Contamination of greywater:** aggressive cleaners (e.g., strong disinfectants, drain cleaners) that are either employed or disposed of in the building will mix with standard greywater, modifying its composition and potentially damaging plants and/or microbial biofilms. However, results from NICE stress tests indicate that the absence of damage if the following products are employed: bleach, floor cleaner, drain cleaner. Sodium hydroxide in granular form was also tested, as it is sometimes employed as a homemade drain cleaner.

Routine operation and maintenance tasks

- **Remove garbage** that may be abandoned in pots (for green walls in locations open to the general public): as needed.
- **Clean degreaser unit:** once per year.
- **Check for absence of dripping from pots:** 3-4 times per year. If any dripping is spotted, identify the origin and repair it as soon as possible. This should normally be achieved simply by cleaning any clogged irrigation hole.
- **Check for correct functioning of the irrigation system** (e.g., pump working, no clogged irrigation holes): once per year if plants look healthy.
- **Prune plants:** check once per year.
- **Replace dead plants:** as needed.

2.2.7 Alignment with the IUCN global standards

Nature-based Solutions (NbS) implemented within the NICE project are intended to provide not only effective technical performance, but also broader environmental, social, and governance benefits. The IUCN Global Standard for Nature-based Solutions offers an internationally recognised framework for designing, assessing, and scaling NbS, ensuring that such interventions address societal challenges while maintaining ecosystem integrity, economic feasibility, and long-term sustainability.

This section evaluates how the green wall typology for greywater treatment, and its implementation in the Turin NICE Urban Real Lab (URL), align with the eight criteria of the IUCN Global Standard. The assessment identifies current strengths, highlights areas where further development may be beneficial, and proposes actions that could strengthen compliance with the Standard.

Table 2.2.3. presents the alignment assessment for the Turin NICE URL, summarising the status of each IUCN criterion together with supporting commentary and recommended actions to improve alignment. Building on this case-specific analysis, Table 2.2.4 outlines general considerations for aligning green wall systems for greywater management with the IUCN Global Standard. These considerations support the design, implementation, monitoring, and replication of this NbS typology in different urban and building contexts.

Together, the assessment and derived recommendations provide a structured basis for ensuring that green wall systems contribute to sustainable water reuse, urban resilience, and the mainstreaming of decentralised Nature-based Solutions.

IUCN criterion	Status	Commentary	Actions to fulfil or strengthen alignment
C1. Address societal challenges	+	The green wall contributes to water security through greywater reuse and improves urban microclimate and aesthetics.	Link explicitly to city-wide water reuse, climate resilience strategies and drought mitigation targets.
C2. Design informed by scale	±	The system is proven at building scale, but wider replication has not yet been demonstrated.	Test replication across multiple buildings or neighbourhoods with varying usage patterns.
C3. Net gain to biodiversity	±	Biodiversity benefits are mainly related to plant survival and pollinator attraction at small scale. The pilot explores how plant species can simultaneously deliver treatment performance and biodiversity support, testing survival and adaptability under green wall greywater conditions	Expand plant palette and monitor biodiversity indicators beyond vegetation survival.
C4. Economic viability	±	Operation and maintenance costs are low, but a formal cost-effectiveness analysis is limited by scale.	Quantify the economic value of co-benefits (energy savings, insulation, water reuse). Cost-benefit analysis to be carried out for solution implementation in wider scale (neighbourhood, local).
C5. Inclusive governance	+	The system was co-designed with local associations, municipal technicians, and site managers. Stakeholders were actively engaged in design and decision-making. Meetings and transparent sharing of information ensured participation.	Develop governance guidance for implementation in public and semi-public buildings.
C6. Balance of trade-offs	+	Design balances treatment performance, aesthetics, safety, and architectural constraints.	Document trade-offs to support decision-making in different building contexts.
C7. Adaptive management	±	Monitoring focuses on system functioning and plant survival.	Introduce water quality and reuse performance indicators to support adaptive management. Monitoring of indicators and data should inform planning and management of the solution.
C8. Mainstreaming & sustainability	+	The pilot is embedded in the local Strategic Plan for Sustainable Water Management and contributes to Action Plan targets for greywater reuse.	Address regulatory and administrative barriers to support broader uptake.

Table 2.2.3 Alignment of the Turin NICE URL with the eight criteria of the IUCN Global Standards

IUCN criterion	Considerations
C1. Address societal challenges	• *Explicitly define the primary challenge addressed (water scarcity, urban heat, lack of green space) and quantify expected contributions.* • *Frame green walls as multifunctional infrastructure, not only related to its aesthetic value, linking water reuse to climate resilience and public health.* • *Identify co-benefits to strengthen NbS justification, including energy savings, educational value, water reuse* • *Ensure the treated greywater reuse pathway is clearly integrated into local water management strategies.*
	Main societal challenges addressed by this typology:  CLIMATE RESILIENCE | PARTICIPATORY PLANNING & GOVERNANCE | WATER MANAGEMENT | HEALTH & WELL-BEING
C2. Design informed by scale	• *Integrate engineering constraints (load-bearing capacity, fire safety, irrigation reliability) alongside ecological objectives.* • *Develop replicable modular designs that allow scaling from single buildings to district applications.* • *Provide clear operation and maintenance protocols addressing drought periods, irregular inflows, and system shutdowns.*
C3. Net gain to biodiversity	• *Select plant assemblages that balance phyto-treatment capacity with ecological value, prioritizing vegetation species that are pollinator-friendly, native, and drought-tolerant.* • *Avoid monocultures; design for layered vegetation to create microhabitats even in vertical systems.* • *Monitor biodiversity indicators (plant survival, insect presence) alongside water quality and treatment efficiency metrics.* • *Ensure substrate and irrigation regimes support both ecological function and water filtration.*
C4. Economic viability	• *Use multi-criteria cost–benefit assessments that include reduction of energy use, building lifespan protection, and social value.* • *Evaluate long-term Operation and Maintenance affordability, particularly responsibilities for cleaning pretreatment units and replacing components* • *Communicate economic value through lifecycle analysis.*
C5. Inclusive governance	• *Engage building owners, users, utilities, and municipalities from the earliest planning phase.* • *Clarify governance models for installations located at the interface of private buildings and public sustainability goals.* • *Use participatory approaches and co-design to align aesthetic expectations with technical feasibility.* • *Document administrative barriers encountered to inform replication pathways.*
C6. Balance of trade-offs	• *Evaluate trade-offs between water reuse, maintenance, system optimization and. architectural integration.* • *Include contingency strategies and planning for variable greywater supply or temporary building closure.* • *Ensure risk assessments cover structural integrity, moisture control, and user safety.*

Table 2.2.4 Key Considerations for the Alignment of Greenwalls for Greywater Management with the IUCN Global Standards

IUCN criterion	Considerations
C7. Adaptive management	• *Establish monitoring frameworks that evaluate multifunctionality* • *Establish monitoring schemes of biodiversity indicators, vegetation health, replacement rates, as well as water reuse volumes, water quality parameters and insulation effects of the NbS* • *Allow flexibility to recalibrate hydraulic loading or plant composition over time, informed by monitored data* **Relevant indicators of NbS performance and impact to be considered for Greenwalls for greywater treatment:** *Climate resilience:* *1.1 Total carbon removed or stored in vegetation and soil per unit area per unit time [kg/ha/y]* *1.3 Monthly mean value of daily maximum temperature (TXx)–wall surface [°C]* *1.4 Monthly mean value of daily minimum temperature (TNn) – wall surface[°C]* *1.5 Heatwave incidence: Days with temperature >90th percentile, TX90p – wall surface [No./y]* *2.1.3 Total leaf area [m^2]* *2.2 Energy use savings due to NbS implementation [kWh/y]* *2.17 Rate of evapotranspiration [mm/day]* *Water management:* *3.2 Water quality:general urban* *3.3: Water quality: TSS content [mg/L]* *3.6: Water quality: total faecal coliform bacteria content of NbS effluents [No.]* *4.19 Rainwater or greywater use for irrigation purposes [m^3/y]* *4.38: Water quality: basic physical parameters* *Green Space management:* *7.2 Share of green urban areas [Number (0-1)]* *Biodiversity Enhancement:* *9.2 Number of native species [No.]* *9.3 Number of non-native species introduced [No.]* *Place regeneration:* *13.6 NbS incorporated in building design / incorporation of environmental design in buildings [Number (0-5)]* *Knowledge and Social Capacity Building for Sustainable Urban Transformation:* *15.1 Citizen involvement in environmental education activities [No.]* *16.1 Children involved in educational activities [No./ y]* *Health and Wellbeing:* *22.12 Visual access to green space [Number (0-4)]* **Evaluating the Impact of Nature-based Solutions: A Handbook for Practitioners (EC, 2021)*
C8. Mainstreaming & sustainability	• *Embed green wall systems into urban water reuse regulations, building codes, and climate adaptation plans.* • *Translate pilot findings into technical guidelines accessible to architects, planners, and utilities.* • *Highlight the role of decentralized circular water systems in urban areas* • *Use demonstration sites for knowledge transfer to build institutional confidence*

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2.3

Mixed multi-stage treatment wetlands for Greywater and stormwater treatment

Algeciras, Spain

2.3.1 Introduction
2.3.2 Required data before designing a project
2.3.3 Design
2.3.4 Design example
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2.3.6 Management, operation and maintenance
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2.3.1 Introduction

In the face of growing environmental challenges, the management and treatment of stormwater and greywater are increasingly recognized for their importance in reducing pollution, mitigating flood risks, conserving water resources, and promoting ecological health. Stormwater, which results from precipitation events, can carry a variety of pollutants from urban surfaces into waterways, while greywater, wastewater from sinks, showers, and laundry, represents a significant portion of domestic water use that can be reused if treated properly.

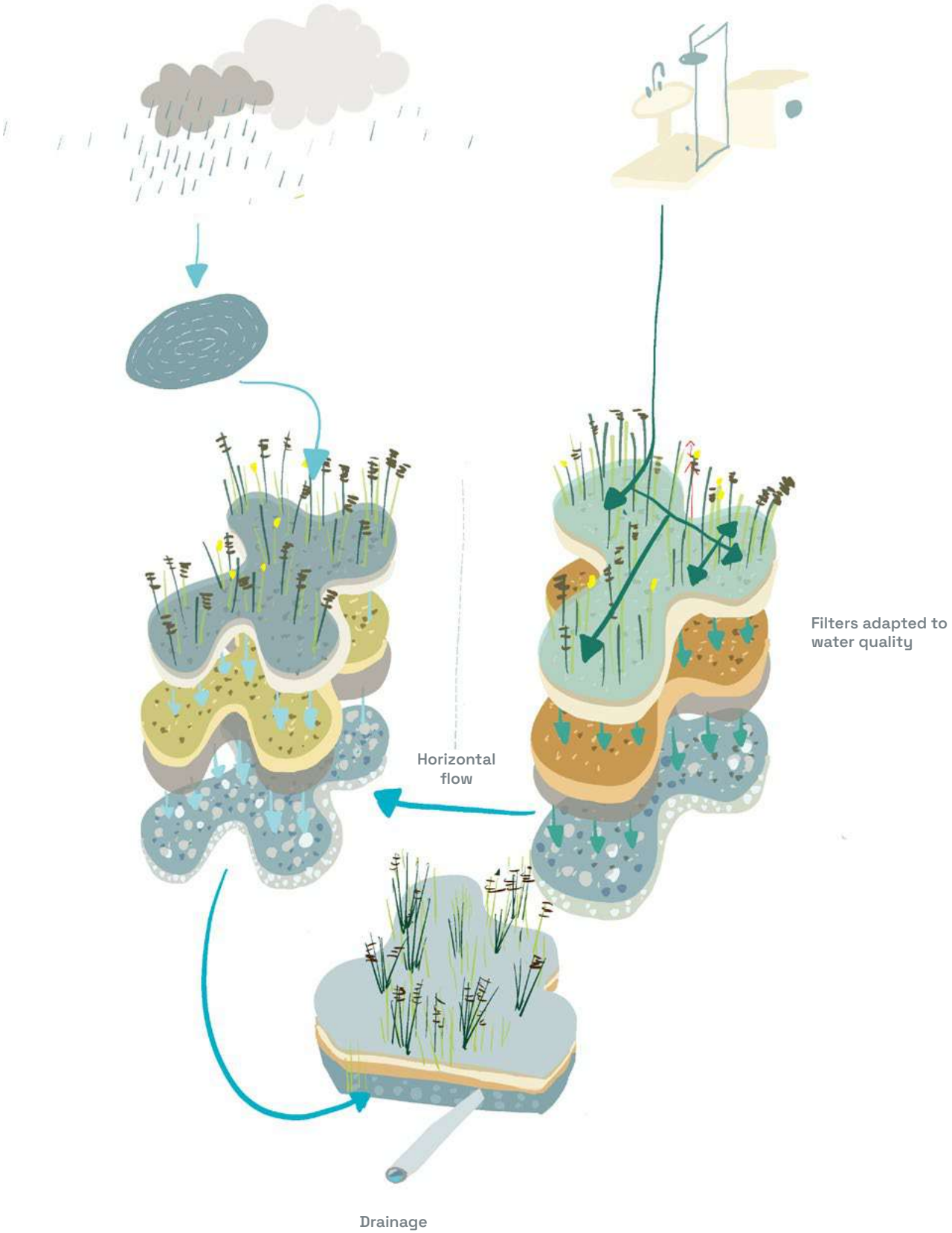
Definition and scope

Mixed Multi-Stage Treatment Wetlands consist of engineered systems that operate following a series of interconnected wetland stages. Their innovative design and dimensions were primarily studied and developed for installation in a temperate Mediterranean climate with hot summers, low rainfall and mild winters with higher rainfall.

Here, during periods of prolonged drought, the vegetation systems may suffer from water shortages, which are compensated for in this filter configuration by the supply of grey water, which is also treated within a single treatment unit. This innovative configuration thus achieves the dual objective of treating and reusing stormwater and grey water, adapted to hot or temperate climates.

These could integrate both horizontal flow and vertical flow treatment wetlands into a single unit, enhancing pollutant removal efficiency while contributing to biodiversity and environmental resilience (Awasthi et al. 2023; Sijimol & Joseph, 2021). However, the successful implementation of these systems requires careful consideration of design, operation, and maintenance.

Challenges like varying flow rates, seasonal changes in pollutant loads, and the need for ongoing maintenance can impact the effectiveness of treatment wetlands. Therefore, effective tools and guidelines are needed to ensure sustainable water management and environmental protection.


STORMWATER
GREYWATER
Filters adapted to water quality
Horizontal flow
Drainage

2.3.2 Required data before designing a project

1. EXISTING INFRASTRUCTURE

This includes drainage and other hydraulic networks. When understanding the existing infrastructure should consider:

- *location, dimensions, and flow capacity of stormwater drainage sewers and culverts for stormwater, and the number of washroom sinks, showers, laundry machines, kitchen sinks and so on from which greywater will be collected;*
- *watershed collected by the stormwater pipe, i.e., conditions of adjacent surfaces (roads, sidewalks, etc.), including distinctions between permeable and impermeable areas, which directly influence runoff coefficients.*

2. AVAILABLE LAND, ITS CHARACTERISTICS AND DETAILS

Available superficial land could potentially impose technical limitations for the installation of the filter and storage basins if necessary. Therefore, spatial identification and detailed mapping of superficial terrain and underground utilities, including potable water supply, wastewater system, gas mains, electrical and telecommunication cables, is critical to avoid conflicts and ensure safe construction.

The footprint of the system depends on several parameters:

- *the volume of rainwater to be treated at peak times (annual rainfall, ten-year rainfall, etc.);*
- *the authorized leakage flow (the higher the leakage flow, the less space the retention area will occupy);*
- *the available difference in elevation between the inlet water level and the outlet water level (in the case of gravity-fed operation);*
- *It should be noted that the total land area required for the installation is equivalent to twice the filter surface area.*
- *Where possible, ensure that the basin operates by gravity to avoid installing a pump station. If this is not possible, install a pump downstream of the basin to discharge into the natural environment rather than a pumping station upstream of the filter.*
- *The system requires a minimum height difference of 1 meter between the surface of the filter and the outlet water line, plus the desired maximum storage height.*

3. WEATHER, CLIMATE AND HYDROLOGICAL CONDITIONS

Treatment wetlands must be designed considering common climatological conditions and stormwater inflows that should be modelled considering the rain reference event to be stored and treated to perform as expected. When understanding the weather, climate and hydrological conditions, consider:

- *historical precipitation records and intensity, duration, and frequency data for the site;*
- *runoff volumes and flow from catchment modelling;*
- *groundwater depth and soil layers to assess risks of submergence.*

4. STORMWATER AND GREYWATER POLLUTION SOURCES, QUALITY AND QUANTITY

The design of the treatment wetland must consider the inlet contaminants concentration and expected pollutants in the influent. Some of these include:

- *common contaminants like suspended solids (TSS), organics (BOD_5, COD), nutrients (N, P), PAHs, heavy metals, pathogens, and contaminants of emerging concern (CECs), whether there is an issue for the latter;*
- *for stormwater, identification of pollution hotspots: roadways, industrial zones, parking areas, or areas with pet waste;*
- *For greywater, it depends on whether kitchen facilities are connected or not to the drainage network, as its pollutant composition notably changes and may require different design or additional pre-treatment steps.*

5. RECEIVING ENVIRONMENT

- *data on the receiving environment (knowledge of low water flow, for example, knowledge of the quality of the environment, etc.).*

6. RISK AND HAZARDS

The design of the treatment wetland should consider risks and hazards, mostly regarding environmental conservation and ecosystem services. Collected data should include:

- *Evaluation of existing ecosystem services in the pilot area, such as microclimate regulation, pollutant buffering, and recreational value.*

7. REGULATORY CONSTRAINTS AND LEGAL FRAMEWORK

Legal and cultural context may define design boundaries, including:

- *Regulatory data on discharge into the environment in terms of quantity (regulatory discharge flow rate) and quality, according to the impact on the environment.*
- *Presence of heritage-protected buildings or archaeological areas;*
- *Compliance with national or EU legislation related to construction, water reuse, and biodiversity conservation (e.g., EU Water Framework Directive, IUCN Global Standard for NbS).*

The parameters described in this section constitute the mandatory input dataset and are subsequently applied in the design example presented in the "Design Example".

2.3.3 Design

The design of this system is based on separate sizing of the rainwater filter and the grey water treatment filter, which will be implemented within a single filter. All design criteria, hydraulic assumptions, and material specifications described in this section are consistently applied in the practical design example presented later in this section.

If the rainwater filter is designed to both treat and mitigate the flow of the rain reference event considered for designing, this volume can be stored either in a separate structure upstream of the filter or directly above the surface of the filter. However, the latter option could require a filter with a surface storage height of up to 3 m. It should be noted that for regulatory reasons, if the filter is located in a space open to the public, it may be necessary to minimize surface ponding for safety reasons and, therefore, to consider an underground storage basin upstream, which is the case in the design example described below.

Stormwater treatment wetland

Among the different types of vegetated filters, the use of vertical flow treatment wetland (VFTW) for the treatment of stormwater runoff is particularly developed. Indeed, vertical flow TW (VFTW) are less sensitive to hydraulic load variations and clogging than horizontal flow TW. VFTW have in addition, the advantage of combining a treatment function and a storage capacity (Molle et al., 2014).

The functioning principle consists of the infiltration of the stormwater runoff through a filtration zone made up of several layers: the filtering layer, the transition layer, and the drainage layer (Figure 2.3.1). As the TWs are watertight, the percolated water is then collected and conveyed to the natural receiving environment through a drain placed at the bottom of the filter.

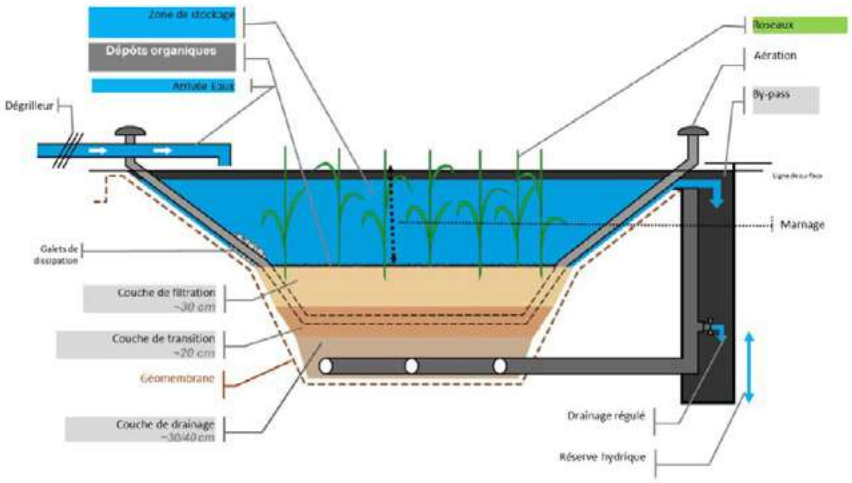


Figure 2.3.1

Schematic cross-section of a reed bed filter for treating urban wastewater during rainy weather. Source: SEGTEUP (Molle et al., 2014).

The flow in the filter is gravitational and depends on several factors specific to the characteristics of the filter (permeability of the medium, outlet regulation flow rate, ...).

In terms of the treatment process, stormwater TWs involve two main mechanisms:

- **Physical filtration**. Since most of the stormwater pollution is in particulate form (carbonaceous pollution, trace metal elements, polycyclic aromatic hydrocarbons -PAHs-), the filtration role of these structures is essential for treatment. Macrophytes improve the physical filtration capacity by preventing clogging of the upper layers by suspended solids -TSS.
- **Biodegradation and biochemical oxidation** by microorganisms of organic or nitrogenous matter.

Four phases took place during a rain event:

- a phase of **progressive saturation of the filter**, which will depend on the initial state of saturation, the characteristics of the rain event and possible preferential paths of flow;
- a phase of **complete saturation of the filter a**nd water storage above the surface (only 5 cm maximum in the Algeciras design, as the storage capacity consists of an upstream underground storage tank). The duration of this phase impacts the dissolved oxygen content inside the filter.
- a phase of **desaturation and reoxygenation of the filter**;
- **a "dry" phase** where the water in the bottom saturated zone (water reserve) rises by capillary action according to the evapotranspiration of the reeds. This water reserve is essential for the reeds' survival and is generally 30 to 40 cm depth depending on the climatic region.



Figure 2.3.2

Hydr'Epur® process – EcoBIRD 3D cross sectional view

Determination of the daily reference volume to be treated

A statistical analysis of the stormwater flows to be treated (intensity, duration, frequency) will make it possible to set, in comparison with the sensitivity of the environment, the daily flow taken as a reference in the design of the structure.

Determination of the technical feasibility of TWs

The technical feasibility of the structure is based primarily on a comparison of the daily flow to be treated and the leakage flow authorized by the water police. Since the objective is to desaturate the filter over 24 hours, if the daily flow to be treated is greater than the authorized leakage flow over 24 hours, the technical feasibility of the FPRs is to be questioned. In borderline cases, the daily volume can be redistributed over 30 hours, but beyond that, another technical or geographical solution will have to be considered.

Once the technical feasibility of the structure has been validated, its dimensions must be determined through the hydraulic dimensions, which will also guarantee the performance in terms of COD, TSS, and BOD_5 parameters (hydraulic shortcuts or clogging,..).

Determining the filter's surface

- The design is done to treat a certain volume per rainfall event (monthly or annual return period rainfall, etc.) according to the local characteristics of the rainfall event.
- Once the maximum daily volume to be treated has been determined, the filter configuration must be sized from a hydraulic perspective.
- The hydraulic design of the treatment wetland is therefore based on different phases (see Figure 2.3.3) aimed at determining the filter surface area, storage volume, overflow height, and reserve height at the base of the filter.

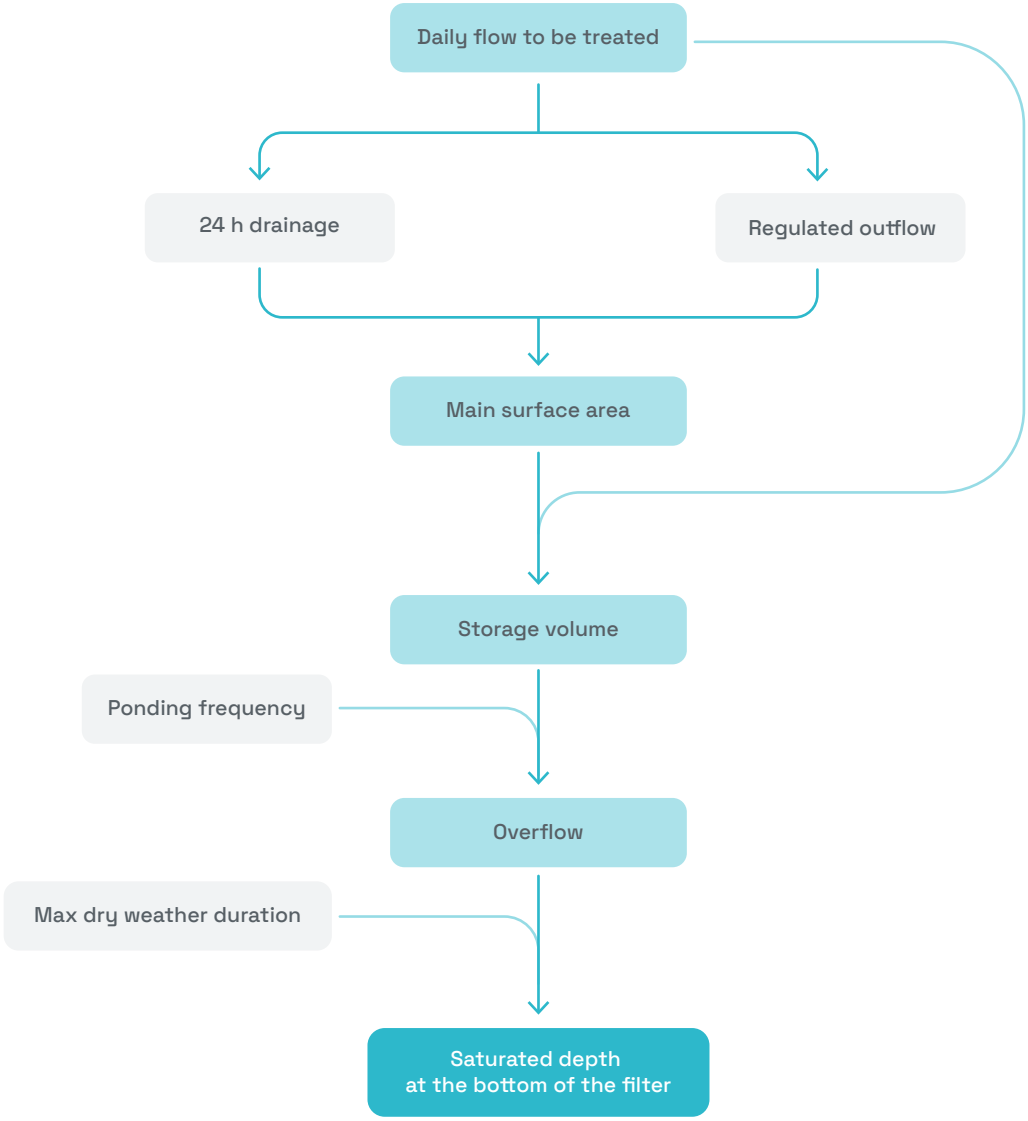


Figure 2.3.3

Hydraulic design methodology for stormwater Treatment Wetland

The main design criteria that drive the filtration area, considering the targeted rain event and associated volume, are:

- **Annual HL based on data series**
  Maximal Annual hydraulic loading rate of 100 m/year for strict storm water runoff and 50 m/year for CSO.
- **Annual SS loads to avoid clogging**
  Maximal annual fines, Suspended Solids loading of 7 kg/year (Grotehusmann et al, 2015)
- **The duration of filter emptying**, considering the targeted rain event (intensity/duration curves)

  Total emptying of the extreme rain event (design event) within 24 h, considering a maximum infiltration rate of 1.10-5 to 5.10-5 m/s, is needed to ensure removal efficiency, and that must be calibrated at the outlet (calibrated outflow).
- **The maximum volume storage constraint**
  - *Maximum plants submersion height as a function of the occurrence (see graph Figure 3.3.4).*
  - *Storage capacity above the filter or in an upstream storage basin, in accordance with the targeted rain event*
- **The maximum authorized outflow** is up to the flood mitigation regulation

Minimum filter surface area

The minimum filter surface area is linked to the drainage in 24 hours (exceptionally 30 hours) of the reference volume to be treated at a certain drainage rate. To this end, the study conducted as part of this project recommends regulated drainage rates between 1.10^{-5} and 5.10^{-5} m/s. The filter surface area is therefore calculated using the following formula:

$$S_{minhyd} = \frac{Q_{dayref}}{V_{Drain \times 86400}}$$

With Smin hyd, the minimum filter area based on hydraulics (m^2)

Qdayref, the reference daily flow to be treated (m^3/day)

VDrain, the regulated drainage velocity (m/s)

In order to avoid any ponding onto the stormwater filter, it is also possible to store the runoff water upstream of the filter in a dedicated storage tank or basin (open air or underground) and feed the filter with small batches. In this case, the calculation of the area remains the same.

Storage volume and ponding height (if stored volume above the filter)

The storage volume of the treatment structure must be sufficient to accommodate the reference rain event volume. It should be noted that storage takes place:

- in the porosity of the medium
- on the surface of the filter, or in a dedicated upstream storage tank.

The calculation of the storage volume available in 24 hours in the porosity of the medium must take into account the geometry of the structure (slope of the embankments under the gravel). Assuming vertical walls at the level of the materials, the surface storage volume in 24 hours can be calculated using the following equation:

$$V_{surf\ storage} = V_{ref} - S_{filter} \times h_{media} \times porosity$$

However, the storage volume can also be evaluated more accurately using the "rainfall method", which incorporates the variation in rainfall intensity over the period considered and also takes into account the discharge rate of the structure.

The maximum ponding height is linked to the authorized frequency of reed submersion in order to avoid any problems with rotting. Here again, a dynamic hydraulic analysis (using rainfall records over long and significant periods prior to the reference event) would allow for more precise designing, since water is drained during rainy periods. From a safety perspective, and with reference to the observations conducted on the previous project (Molle et al., 2014), we can perform static design based on Figure 2.3.4.

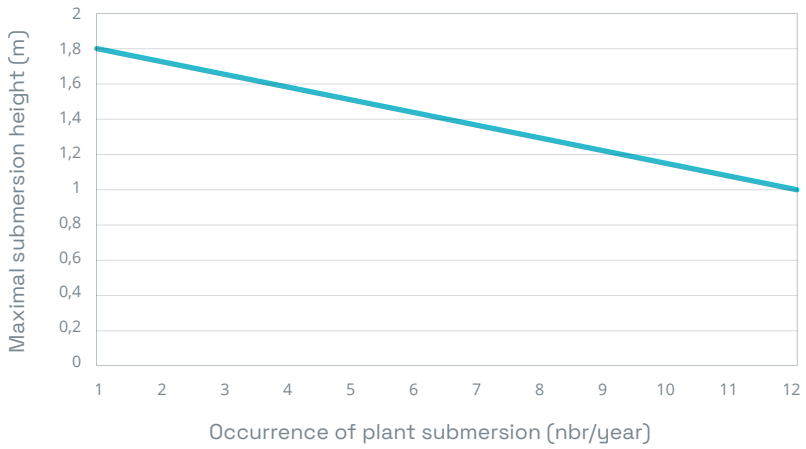


Figure 2.3.4

Permitted submersion height based on the occurrence of rain events (Molle et al., 2014)

The geometry of the basin must therefore allow both the storage of the rain event reference volume and a frequency of submersion compatible with the survival of the reeds.

In the case of storage in a structure upstream of the filter (underground basin), the capacity of the basin must be sufficient to hold the reference rainfall volume to be treated. The water will thus be discharged onto the filter for treatment by pumping during the event using a supply system that ensures even distribution across the surface of the filter and a pumping flow rate of around 0.5 $m^3/h/m^2$.

Determining the filter's material

This subsection will present the material type and depth to reach the described removal efficiencies.

Filter media composition from the top to the bottom:

Filtering layer: 30 to 40 cm of 0/4 mm sand,

The characteristics of the sand are as follows:

- *0.25 mm< d10< 0.40 mm*
- *3< Cu < 4 (Uniformity Coefficient= d60/d10),*
- *Fine content (Φ< 63 µm) less than 2.4% by mass (d< 63 µm), (d<80 µm) less than 3% by mass*

Transition layer: 15 cm of 2/6 to 3/8 mm gravels, receiving the intermediate aeration network,

Drainage layer (including water reserve): 30-40 cm of 10/20 to 15/25 mm, receiving the drainage network.

The height of the saturated zone at the bottom of the filter serves as a water reserve to ensure that water rises by capillary action to the rhizosphere. Studies conducted on the hydraulic model of these systems have shown that a reserve of 20 to 30 cm maximum is more than sufficient to ensure the survival of reeds in the French context.

For the retention of micropollutants by adsorbent material, it is recommended to place this layer of active media stacked between two layers of sand. The thickness of this layer, preferably with a particle size similar to that of the sand filtration layer, will be determined according to its maximum adsorption capacity of the targeted pollutants and the desired lifespan before the material needs to be replaced.

Treatment performances for storm water runoff for COD, BOD_5, and TSS of 65%, 70% and 90%, respectively, should be achieved with the following filtering material composition and based on hydraulic design specifications described above.

Parameters	Expected removal efficiency	OR	Expected outlet concentration (mg/l)
TSS	**90%**		10
COD	**65%**		30
BOD_5	**70%**		20

Table 2.3.1

Expected outlet concentration and removal efficiencies for stormwater runoff filter (without reactive media).

Greywater treatment wetland

The approach developed here consists of the implementation of a raw grey water treatment directly on a single unsaturated-saturated treatment wetland continuously fed (without alternation). This configuration includes a deep bed depth in order to pile an unsaturated zone (30-40 cm deep) on top of a saturated zone (30 cm deep), which is common with a stormwater filter. The unsaturated upper part is mainly designed according to the clogging limits given for a sand filter. It ensures the filtration of suspended solids and aerobic treatment of the dissolved pollution, while the saturated lower part, filled with coarse gravel, allows denitrification and concomitant organic carbon removal. It also retains the remaining TSS (mainly detached biofilm). At the interface between the unsaturated and saturated zones, aeration pipes allow oxygen transfer to the bottom part of the unsaturated zone.

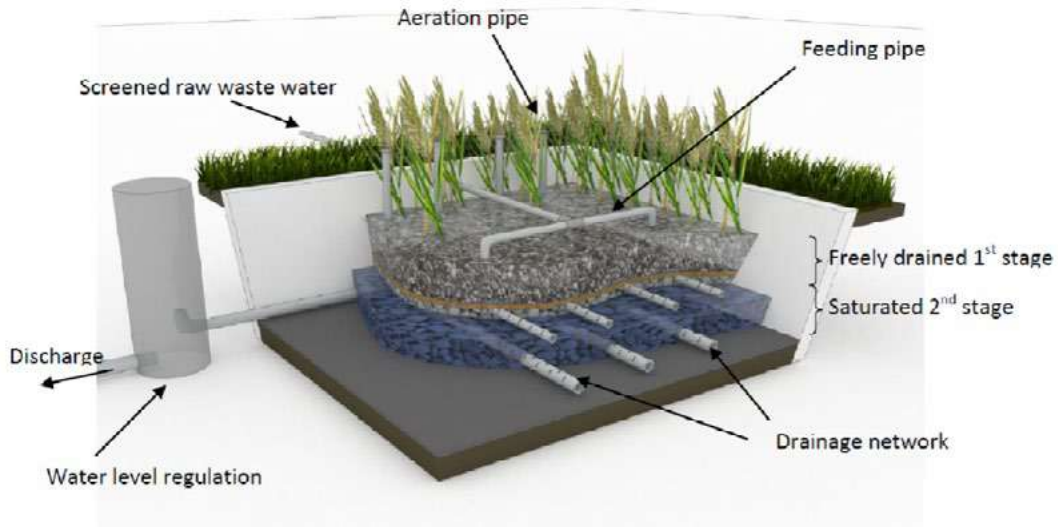


Figure 2.3.5

3D cross section of a Biho-Filter® (EcoBIRD).

Determining the filter's surface

The filter surface continuously fed by gray water is determined by an optimized equilibrium between hydraulic and organic load. The loads received must obviously be quantified in advance, both qualitatively and quantitatively, up to the type of grey water collected.

As an example, we will use a maximum organic load of 15-20 g $BOD_5/m^2/day$ for a maximum hydraulic load of 0.3 - 0.4 $m^3/m^2.d$.

The most discriminating factor between organic and hydraulic loading rates will be used to determine the filter surface area.

Determining the filter's Material

Here, for the TW mixed multi-stage system, the composition of the filter treating gray water is similar to that of the rainwater filter, with:

- *An unsaturated filtering layer over 30 cm, made of either sand (same quality than stormwater TW) only or 20 cm of sand and 10 cm of specific adsorbent for micropollutant removal if required*
- *15 cm of transition layer made of gravel with intermediate aeration pipes (2/6 to 3/8 mm)*
- *30 to 40 cm of saturated coarser gravels (10/20 to 20/40 mm) in which are located drainage pipes. In addition to the treatment mentioned above, this layer also acts as a water reserve in the event of prolonged drought, with a regular supply of treated grey water to the saturated zone of the rainwater filter due to its hydraulic connection.*

The choice of the filtration support is essential because it must allow the good development of the biomass while minimizing the risk of clogging.

For this purpose, 0/4 mm sand is used (see specifications above), ensuring an optimal specific surface for biofilm fixation and a sufficient porosity for the flow.

In order to ensure a homogeneous distribution of the effluent across the filter surface, it must be applied in a 2 cm hydraulic load at a flow rate of 0.25 $m^3/h/m^2$ using a distribution ramp system.

The inlet concentrations, expected outlet concentrations and removal efficiencies during dry weather flow are given in the table below.

Parameter	Inlet concentration (mg/L)	Outlet concentration (mg/L)	Removal efficacy (%)
TSS	130	10	90%
COD	500	70	85%
BOD_5	250	20	90%
TKN	10	5	50%

Table 2.3.2

Expected outlet concentration and removal efficiencies of the filter with greywater.

2.3.4 Design example

A practical design example of a Mixed Multi-Stage Treatment Wetland that was implemented within the NICE project for the Algeciras demonstration Urban lab is presented below, providing insights into the intricate design elements and operational principles that contribute to the successful treatment of stormwater and greywater.

The climate of Algeciras (south of Spain) is transitional between oceanic and Mediterranean climates. Rainfall is distributed unevenly throughout the year, with heavy rains in winter and dry summers. Figure 2.3.6 describes the overall plan of the innovative treatment wetland receiving both stormwater runoff and grey water.

The innovative design consists of a filter receiving both stormwater runoff and greywater and combining a vertical/horizontal flow system. The main goal of this configuration is to maintain a permanent water level inside the filter, within the horizontal flow zone, ensuring the biomass and plants survive during long dry periods. As described in the picture below (Figure 2.3.7), each type of wastewater has its own vertical filtration filter and a common horizontal flow filter until the outlet.

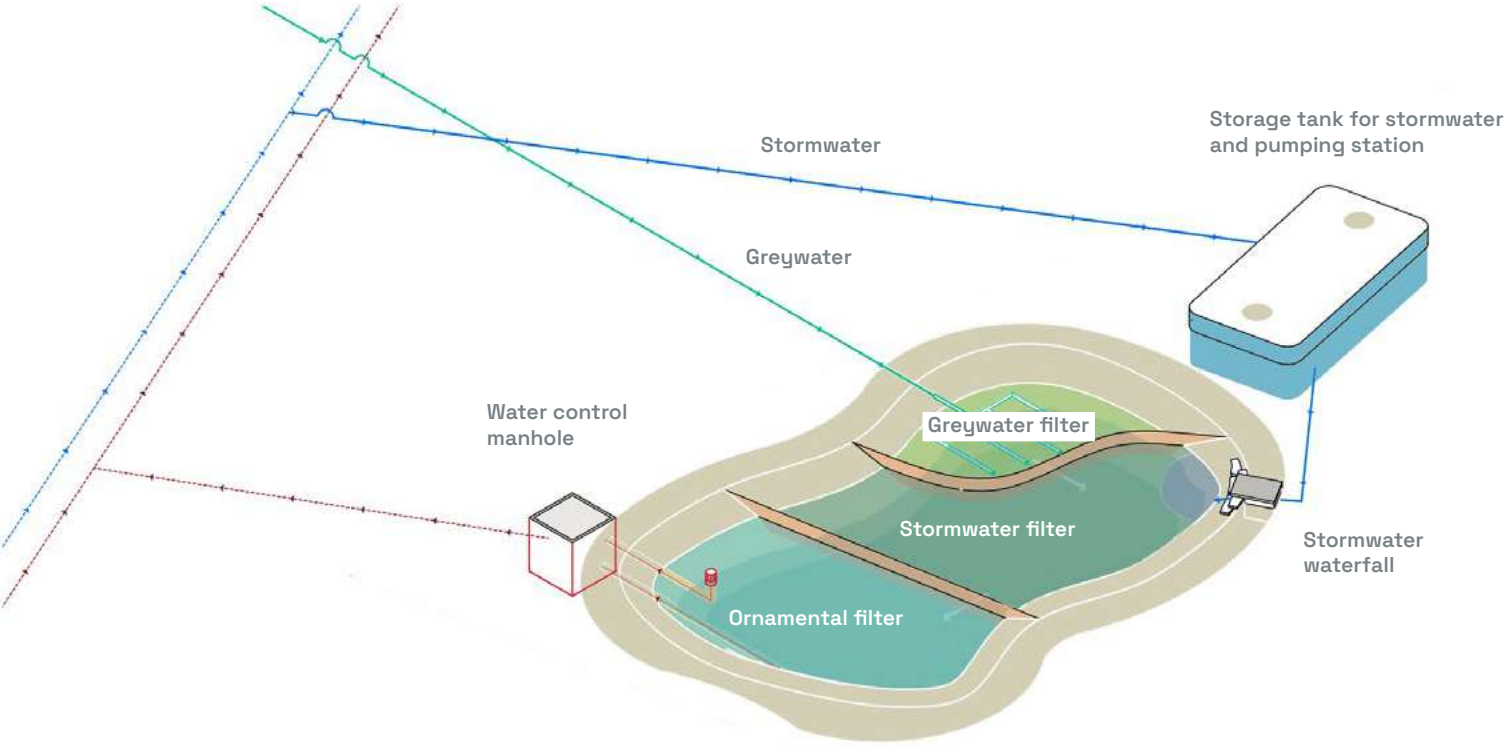


Figure 2.3.7

Schematic diagram of the Algeciras Urban Real Lab

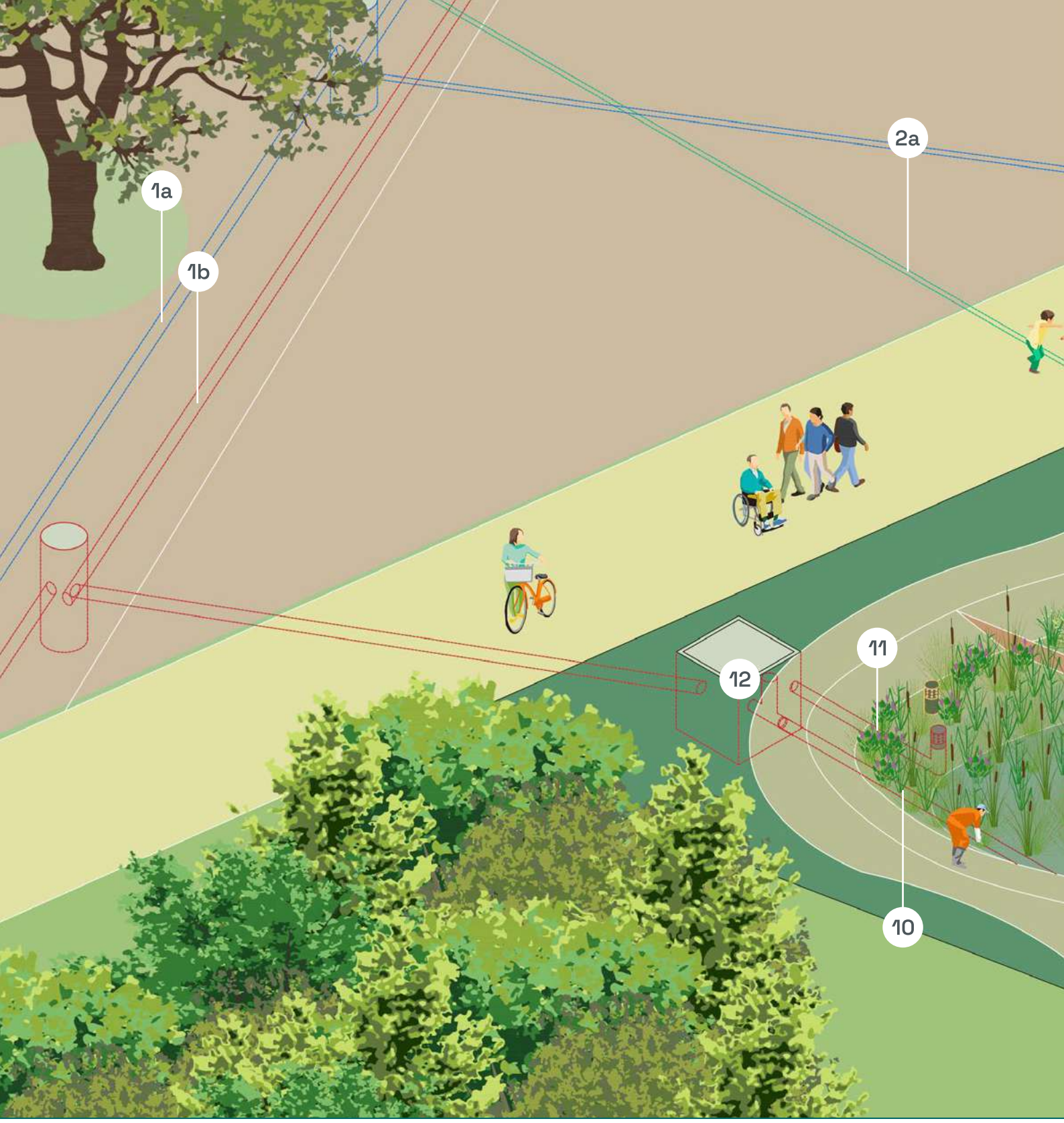


Figure 2.3.6

Schematic layout of the treatment wetland system for storm water runoff and grey water treatment in Algeciras.

- 1a Stormwater sewer
- 1b Sewer
- 2a Greywater
- 2b Greywater feeding network (High-Density Polyethylene)
- 3a Stormwater
- 3b Storage tank for stormwater (20m³) and pumping station (2 pump flows 15m³/h)



4 Stormwater waterfall

4a Stormwater inlet

4b Jet breaker manhole

4c Waterfall rocks

4d Protection gravel for the waterfall

5 Greywater filter (15 m²)

6 Stormwater filter | Hydr' Épur (40 m²)

7 Ornamental filter (30 m²)

8 Separation wall

9 Ventilation chimney

10 Drainage pipe

11 Overflow

12 Water control manhole

Stormwater Treatment Wetland design

The catchment area assumed is an impervious area of 8500 m^2. The runoff coefficient is assumed to be 0.7, which gives an active surface area of the catchment of 5950 m^2

The average annual rainfall in Algeciras for the last ten years is 484 mm/yr with a standard deviation of 136 mm/yr and a maximum of 791 mm/year in 2018. The reference rainfall used for dimensioning is a rainfall with a return period of 1 year, equivalent to a daily precipitation of 20 mm. The intensity curve for this rainfall is provided in the chart below (Figure 2.3.8).

The cumulative average precipitation of rainfall with a lower height than 20 mm is 400 mm, conducting to an average annual flow of 2400 m^3/year.

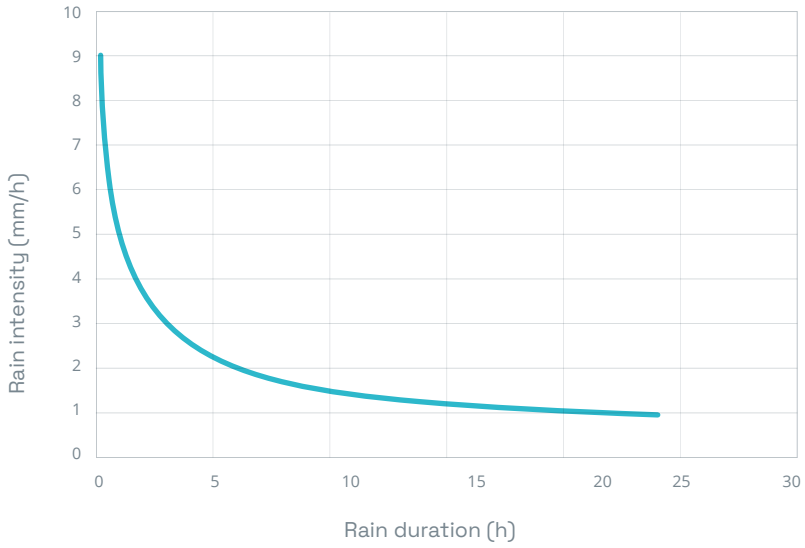


Figure 2.3.8

Rain intensity as a function of its duration for a 20 mm/d rain precipitation in Algeciras (Spain)

The volume of the reference rainfall to be treated is thus calculated at 20 x 5 950 = 119 m^3.

The minimum filter surface area to be used is calculated as follows.

$$S_{minhyd} = \frac{Q_{dayref}}{V_{Drain \times 86400}} = \frac{119}{5.10^{-5} \times 86400} \approx 30m^2$$

With Smin hyd, the minimum filter area based on hydraulics (m^2)

Qdayref, the reference daily flow to be treated (m^3/day)

VDrain, the regulated drainage velocity (m/s)

The average annual hydraulic load would be 2400 / 30 = 80 m/yr, acceptable for strict stormwater runoff.

Here, the calculated storage volume would be 115 m^3, leading to an excessively high storage height of 115/30 = 3.8 m (maximum storage height of 2 m) on the filter and would require either an increase in the filter surface area or additional storage by extending the basin or adding an independent upstream basin/storage tank.

Moreover, this approach does not take into account the hourly flow rate that can be processed by the filter or variations in flow rates depending on the intensity and duration of the rainfall. We therefore propose using the rainfall method, which consists of evaluating the volume to be stored (either on the surface of the filter or upstream) according to the duration of different rainfall events based on the intensity/duration curve.

The chart below gives the storage capacity needed up to the rainfall method and considering a 30 m^2 filter with a calibrated outflow at 5,3 m^3/h (V Drain = 5.10-5 m/s).

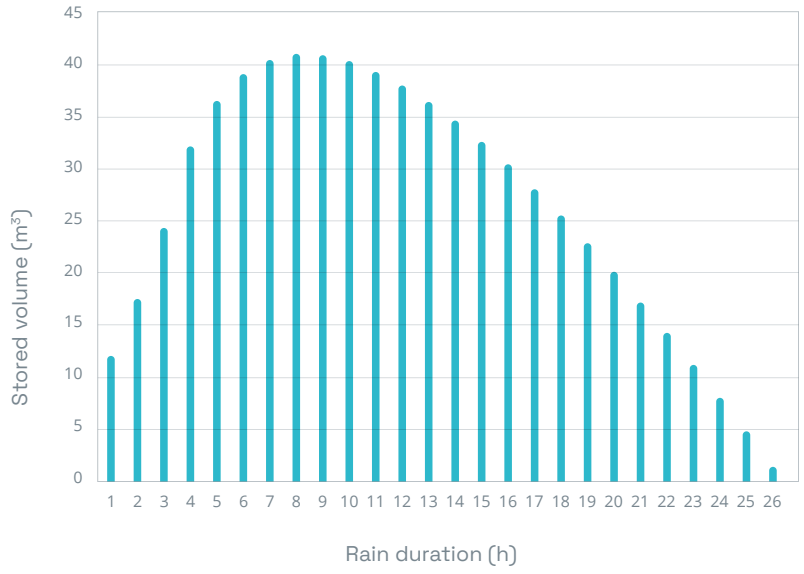


Figure 2.3.9

Storage capacity as a function of the rain duration for a 20 mm/d rain event (design rain).

Therefore, according to this method, the storage volume required would be around 40 m^3, which would result in a storage height of 1,5 m considering a 30 m^2 filter, which is acceptable.

However, in the case of Algeciras, the specifications stipulated that any flooding/ponding of the filter should be avoided, as the filter is located in a space open to the public. Therefore, an underground storage tank of 40 m^3 equipped with pumps, into which the rainwater network discharges, was considered here. The filter would, in any case, be fed by pumping, given that the area is flat.

Once the storage tank is full (return period higher than the reference rainfall), the excess flow will be bypassed.



Figure 2.3.10

Installation photo of the storm water run off storage tank (top) and wetland basin for storm water treatment (bottom).

Greywater Treatment Wetland Design

Greywater to be treated will be collected here from a nearby school, which hosts about 1300 students plus about 50 faculty members. This is equivalent to an average of 2 m^3/day during the opening period (not all sinks are connected to the separative greywater treatment). The water coming mainly from hand washing sinks has an expected quality of 150 mg O_2/L for BOD_5. The daily organic load is thus assumed to be 0.3 kg/d of BOD_5. Considering a unique planted sand filter without alternation, a maximum 20 g BOD_5/m^2xd organic load is recommended to avoid any risk of bioclogging.

Thus, this design organic load led to a total filtration area of 15 m^2 and an HLR of 0.13 m/d. The filter, considering these loads, could be operated continuously without alternation (resting period).



Figure 2.3.11

Installation photo of the wetland basin for grey water treatment.

Dry weather conditions

The filter will have a bottom storage capacity of 40 cm of water saturated, which will compensate for the water loss due to evapotranspiration during the dry period.

The maximum evapotranspiration is estimated to be around 2 cm/ d and may lead to a daily water loss of 1m^3/d with a 45 m^2 total filter area.

This water loss by evapotranspiration will be largely compensated by the greywater to the extent that they are estimated at 1.5 m^3/d.

During summer holidays, if no greywater is available (coming from the university), the saturated bottom zone will enable the supply water for around 1 month before the plants will start having water stress.

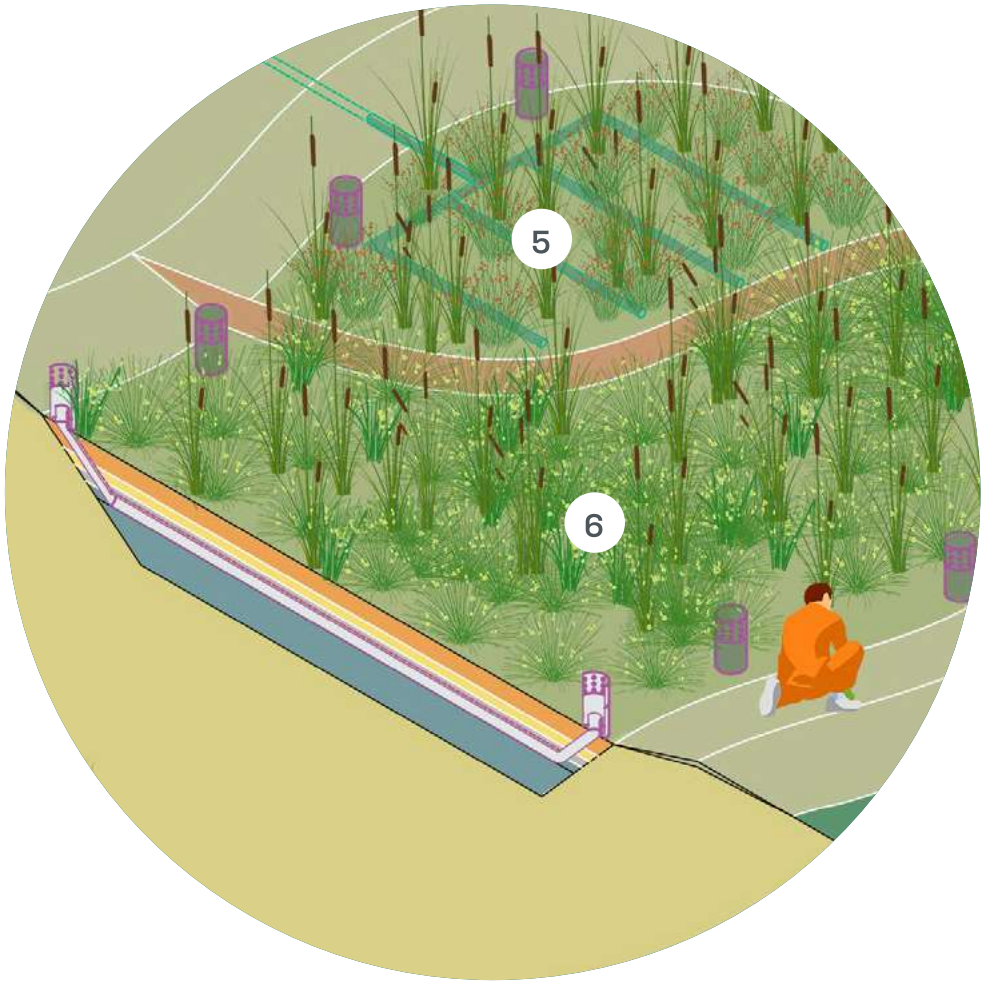
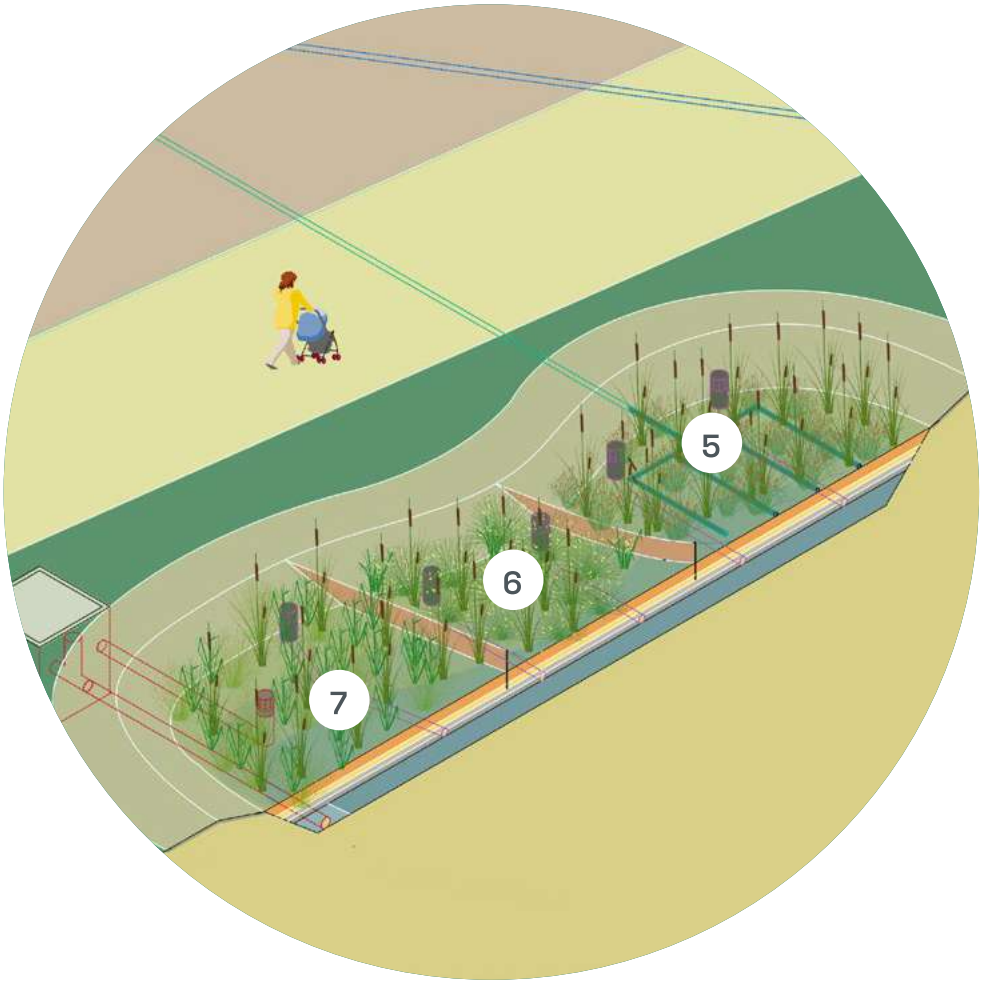


Figure 2.3.12

Cross section of the treatment wetland, Algeciras Urban Real Lab (NICE project).



Algeciras filtration layers composition

The two filters (GW & SW) are separated only on the top surface filtration layer by a 30 cm deep partition wall.

Both filters consist of the following and similar filtration layers:

- An unsaturated filtering layer over 30 cm, made of sand only or 20 cm of sand and 10 cm of specific adsorbent for micropollutant removal (if needed)
- 20 cm of unsaturated transition layer made of gravel with intermediate aeration pipes
- 30-40 cm of saturated coarser gravels in which are located drainage pipes.



Figure 2.3.13

Installation photo of the Algeciras Urban Real Lab (NICE project).

2.3.5 Implementation

The implementation steps described below directly result from the design assumptions and calculations presented in the Design and Design Example sections and do not introduce additional technical requirements.

Implementation of this multi-stage TW for greywater and stormwater involves the following steps:

Site preparation – clearing, excavation, and grading of the area.

This stage begins with a detailed topographic survey to determine slopes and ensure gravity-driven flow between wetland cells. Clearing involves removing existing vegetation, debris, and unsuitable soil layers. Excavation and grading are carried out to create level basins and maintain hydraulic connectivity between stages. Soil permeability tests are essential to prevent unwanted infiltration and protect groundwater resources. Additionally, access paths for maintenance and emergency overflow areas should be planned during this phase.

Construction – earthworks, waterproofing, drain installation, filtering aggregates, filling, etc.

Construction includes shaping sedimentation basins and wetland cells through precise earthworks. Waterproofing is achieved using geomembranes to prevent seepage and contamination of the surrounding soil. Inlet and outlet structures, such as pipes, valves, and flow regulators, are installed to control water distribution and retention times. Drainage systems and overflow channels are incorporated to manage stormwater surges and avoid flooding. Filtering aggregates like gravel and sand are layered to support plant roots, enhance filtration, and promote microbial activity for pollutant breakdown.

Planting – selection and establishment of appropriate vegetation with a minimum density of 4 plants/m² (Phragmites australis in Europe)

Planting focuses on selecting hardy macrophytes adapted to local climate and pollutant loads. Common species include Phragmites australis, Typha latifolia, and Carex spp., which provide efficient nutrient uptake and oxygen transfer to the root zone. A minimum density of four plants per square meter ensures rapid coverage and effective treatment. Planting should be staggered to prevent erosion and allow for uniform growth. During the establishment phase, irrigation and monitoring are necessary to promote root development and prevent plant die-off.

Commissioning – initial inspection, water flow testing, and adjustments

Commissioning involves hydraulic testing to verify uniform water distribution and retention times across all stages. Initial water quality sampling for parameters such as TSS, COD, nitrogen, and phosphorus is conducted to confirm treatment performance. Adjustments to inlet/outlet structures and flow rates may be required to optimize efficiency. This phase also includes operator training on routine maintenance, emergency procedures, and documentation of system performance. Proper commissioning ensures long-term reliability and compliance with company standards.

2.3.6 Management, operation and maintenance

Proper management and maintenance are essential to ensure long-term efficiency.

Although TW are generally low-maintenance compared to grey infrastructure, they still require systematic care to avoid performance decline.

Main operational challenges

- **Clogging:** the irrigation system is slightly more subject to clogging, hence reducing the amount of supplied greywater. This risk is minimised by using perforated pipes for irrigation (see “Implementation”).
- **Sediment clogging:** loss of infiltration capacity due to fine particles.
- **Debris accumulation:** leaves, litter, and trash are blocking inlets/outlets.
- **Vegetation stress or mortality:** caused by droughts, prolonged flooding, or poor species selection. In this innovative configuration, water stress for plants is compensated by a permanently saturated zone at the bottom of the filter.
- **Damage to subsurface infrastructure:** blocked, collapsed, or corroded pipes.
- **Long-term pollutant accumulation:** metals, hydrocarbons, nutrients, PFAS, and other CECs retained in the filter media.

Routine operation and maintenance tasks

STORMWATER FILTER

Frequency	Location	Tasks
As needed	Filter	**During the first year, manually weed the filter as soon as weeds appear. Use the ladder to climb down onto the filter. Cut any woody plants growing on the filter.**
After rainfall	Filter surface / Inlet pipes (if gravity feeding without screening)	**Once the basin is dry, remove any large waste accumulated and dispose of it.**
After rainfall	Filter	Check that the filter has dried out properly after rainfall (within 24 hours of rainfall for annual rainfall). Remove any large debris that may have accumulated.
Twice per year and as needed	Upstream storage tank	Hydroclean the basin and dispose of sludge in an appropriate manner.
Once per year	Reeds (if upstream storage basin only)	Cut and remove old reed stems.
20 years of operation	Filter cleaning / Accumulated sludge excavation	Cut the reeds and then clean the mineralized sludge from the surface of the filter bed. Dispose of the sludge at an approved facility (landfill, incineration).
In the event of accidental pollution	Water level control and containment manhole	Close the manual valve to contain pollution in the basin (accidental spills, fire water, etc.).

Table 2.3.3

Routine operation and maintenance tasks for the stormwater filter

GREY WATER TREATMENT WETLAND

Frequency	Location	Tasks
Once a week	Screening	Empty the contents of the drainage basket into a waste bin.
Once a week	Pumping station	• Check the general condition of the interior of the pumping station (clean with a water jet if necessary). • Check that the pumps are operating alternately. • Check that the piezometric sensor and floats are working properly.
Once a month	Pumping station	Clean the floats' level switch with a water jet.
Once a year	Pumping station	Perform maintenance on the pumps and sensors (according to the manufacturer's specifications).
As needed	Filters	• Weed the filters manually to prevent invasive plants (tomatoes, ragwort, fleabane, grasses, etc.) and encourage colonization by reeds. • Remove undesirable species systematically by manual removal (including roots) at the appropriate time (usually around flowering time to prevent seed dispersal). • Chemical weeding around the filters is prohibited.
As needed	Surrounding area	General gardening: maintain the surrounding area.
Beginning of winter	Filters	• Cut and remove old reed stems using a brush cutter or hedge trimmer. • Move carefully to avoid creating irregularities or damaging underground reeds. • Remove any debris left on the surface during mowing (leaves, stem debris, etc.).
As needed	Filter surface	Remove any leaves deposited on the surface.
Once a year	Distribution pipes	Clean the distribution pipes by unscrewing the caps at the ends and flushing the accumulated sludge.

Table 2.3.4

Routine operation and maintenance tasks for the greywater treatment wetland

2.3.7 Alignment with the IUCN global standards

Nature-based Solutions (NbS) implemented within the NICE project aim to provide not only effective water treatment performance, but also broader environmental, social, and governance benefits. The IUCN Global Standard for Nature-based Solutions offers an internationally recognised framework for designing, assessing, and scaling NbS, ensuring that such interventions address societal challenges while maintaining ecosystem integrity, economic feasibility, and long-term sustainability.

This section evaluates how the mixed multi-stage treatment wetland typology for greywater and stormwater management, and its implementation in the Madrid and Algeciras NICE Urban Real Labs (URLs), align with the eight criteria of the IUCN Global Standard. The assessment identifies current strengths, highlights aspects that may benefit from further development, and proposes actions that could strengthen compliance with the Standard.

Table 2.3.5 presents the alignment assessment for the Madrid and Algeciras NICE URLs, summarising the status of each IUCN criterion together with supporting commentary and recommended actions to improve alignment. Building on this case-specific analysis, Table 2.3.6 outlines general considerations for aligning mixed multi-stage treatment wetlands with the IUCN Global Standard. These considerations support the design, implementation, monitoring, and replication of this NbS typology across different urban and climatic contexts.

Together, the assessment and derived recommendations provide a structured basis for ensuring that multi-stage treatment wetlands contribute to sustainable urban water management, circular water use, and the long-term mainstreaming of Nature-based Solutions.

IUCN criterion	Status	Commentary	Actions to fulfil or strengthen alignment
C1. Address societal challenges	+	The system addresses water scarcity, pollution control, and climate resilience through combined greywater and stormwater treatment and reuse.	Strengthen alignment with regional water reuse and drought resilience strategies.
C2. Design informed by scale	±	The system is designed at a pilot scale. However, its modular, multi-stage configuration allows adaptation to different inflow volumes and scaling to larger catchments.	Demonstrate performance through multiple installations to validate district-scale applications.
C3. Net gain to biodiversity	+	The wetland creates diverse aquatic and semi-aquatic habitats supporting flora and fauna. This contributes to localized biodiversity gains within an urban setting.	Implement long-term biodiversity indicators (macroinvertebrates, vegetation dynamics).
C4. Economic viability	+	Low operational costs and potential water reuse benefits can support long-term cost-effectiveness.	Quantify avoided treatment costs and long-term savings compared to conventional systems. Among the benefits to be considered are the reduction of irrigation water consumption and the reduction of energy costs related to stormwater pumping.
C5. Inclusive governance	+	Local stakeholders, municipal authorities and water utilities are directly involved in system design and operation.	Formalize governance and responsibility frameworks for long-term operation and replication.
C6. Balance of trade-offs	+	Trade-offs between land use, treatment efficiency, and maintenance requirements were explicitly considered. A major risk is related to water availability based on seasonal patterns that can affect the volumes of both greywater and stormwater.	Develop decision-support tools to support site selection in constrained environments.
C7. Adaptive management	+	Monitoring of hydraulic and treatment performance supports adaptive operation. Data on water demand, storage capacity, plant health and nutrient dynamics can guide the adaptive management of the system, ensuring functionality across varying conditions.	Expand monitoring scope to include biodiversity and nutrient dynamics under climate variability.
C8. Mainstreaming & sustainability	+	Strong potential for integration into municipal water management strategies and long-term planning.	Support policy uptake through technical guidelines, operator training, and dissemination activities.

Table 2.3.5 Alignment of the Madrid and Algeciras NICE URL with the eight criteria of the IUCN Global Standards

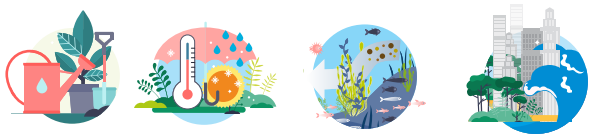
IUCN criterion	Considerations
C1. Address societal challenges	• *Identify the primary water challenge addressed: urban runoff pollution management, run-off management, or alternative water supply generation.* • *Quantify reductions in potable water demand, pollutant discharge, and flood risk.* • *Frame the system as part of urban circular water management, closing local water loops.* • *Highlight co-benefits such as urban greening, climate adaptation, and coastal or watershed restoration.* • *Engage stakeholders early to ensure the NbS responds to locally perceived needs and priorities*
	Main societal challenges addressed by this typology:  GREEN SPACE MANAGEMENT | CLIMATE RESILIENCE | WATER MANAGEMENT | NATURAL & CLIMATE HAZARDS
C2. Design informed by scale	• *Design treatment stages based on expected variability in stormwater and greywater volumes.* • *Integrate hybrid systems, combining Grey infrastructure and NbS to buffer seasonal fluctuations.* • *Size systems to function under intermittent flows typical of Mediterranean climates.* • *Anticipate replication through modular scaling suitable for buildings, districts, or waterfront interventions.* • *Consider the scaling-up of this typology through the enlargement of wetlands when possible, or replication*
C3. Net gain to biodiversity	• *Use plant assemblages adapted to alternating wet/dry regimes to create resilient habitats.* • *Design multi-stage wetlands to support ecological gradients, increasing habitat diversity.* • *Replace or complement grey infrastructure with vegetated systems wherever feasible.* • *Monitor ecological indicators (vegetation health, fauna presence) alongside treatment metrics.* • *Promote ecological connectivity when located near waterfronts or urban green corridors.*
C4. Economic viability	• *Quantify potable water savings from reuse and reduced pumping or centralized treatment loads.* • *Compare lifecycle costs with conventional stormwater management or treatment infrastructure.* • *Emphasize the multifunctionality of treatment wetlands in cost–benefit assessments, including landscape and climate adaptation benefits in addition to water treatment.* • *Use monitoring data to validate operational savings and inform scaling.* • *Highlight reduced long-term operational energy requirements compared to mechanical systems.*
C5. Inclusive governance	• *Involve stakeholders, including municipalities, utilities, and property owners, in the co-design and operational planning.* • *Establish transparent communication on system performance and water reuse safety* • *Use demonstration sites to build acceptance of water reuse practices.* • *Embed NbS and water reuse within existing policy and regulatory frameworks at local, national and EU levels.*
C6. Balance of trade-offs	• *Manage reliance on greywater supply or seasonal stormwater availability and variability.* • *Balance water reuse goals with ecological water needs for vegetation survival.* • *Assess climate related risks (extended droughts, intense rainfall variability).* • *Define maintenance roles clearly to prevent operational uncertainty.* • *Evaluate land-use trade-offs in dense urban settings.*

Table 2.3.6 Key Considerations for the Alignment of Mixed Multi-Stage Treatment Wetlands for Greywater and Stormwater Management with the IUCN Global Standards

IUCN criterion	Considerations
C7. Adaptive management	• *Implement continuous monitoring of inflows, treatment performance, and reuse volumes.* • *Track vegetation condition, nutrient removal efficiency, and seasonal hydraulic performance.* • *Adjust operational parameters (retention time, flow routing) based on observed data and climate variability.* **Relevant indicators of NbS performance and impact to be considered for mixed multi-stage treatment wetlands:** *Water management:* *3.3: Water quality: TSS content* *3.4: Nitrogen and phosphorus concentration or load* *3.6: Water quality: total fecal coliform bacteria content of NbS effluents* *4.1: Infiltration rate* *4.2 Infiltration capacity [mm/d]* *4.3:Rate of evapotranspiration [mm/m^2 day]* *4.5:Flood peak reduction [%]* *4.9: Runoff rate for different rainfall events [m^3/s]* *4.11: Rainfall storage capacity of NbS [mm/%]* *4.19: Rainwater or greywater use for irrigation purposes [m^3/y]* *4.22: Calculated drinking water provision [m^3/ha/y]* *4.24: Volume of water removed from wastewater treatment system [m^3/y]* *4.27: Surface area of restored and/or created wetlands [ha]* **Evaluating the Impact of Nature-based Solutions: A Handbook for Practitioners (EC, 2021)*
C8. Mainstreaming & sustainability	• *Integrate systems into municipal stormwater management, water reuse, or coastal restoration strategies.* • *Develop technical guidance to support adoption in commercial buildings and public infrastructure.* • *Align implementation with regulatory frameworks on water reuse and urban drainage.* • *Promote knowledge transfer between project pilots, utilities, and planners.* • *Position systems as scalable components of urban circular water infrastructure.*

2.3.8 References

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2.4

Vertical-flow treatment wetlands for Combined Sewer Overflow treatment

Lyon, France

2.4.1 Introduction
2.4.2 Required data before designing a project
2.4.3 Design
2.4.4 Design example
2.4.5 Implementation
2.4.6 Management, operation and maintenance
2.4.7 Alignment with the IUCN global standards
2.4.8 References



2.4.1 Introduction

Stormwater management is an important issue for local authorities in order to preserve the receiving environment (surface water and groundwater) qualitatively (pollution control, habitat conservation) and quantitatively (supporting river flows, groundwater recharge). For that, it is essential to limit urban discharges during wet weather as combined sewer overflows (CSOs) which are a mixture of domestic wastewater and rainwaters.

The implementation of treatment wetlands at the point of discharge can be a useful approach to managing hydraulic and pollutant flows, as it can quickly reduce the impact on the water body and avoid high investment costs in sewers or WWTPs. A wide variety of TW have been tested (stormwater ponds, surface flow wetlands, floating treatment wetlands, horizontal and vertical flow treatment wetlands), the main characteristics of which are described in detail in Tondera et al. (2018).

Passive vertical flow TW has been successfully implemented in various countries, including Germany, France and Italy (Meyer et al., 2013; Tondera et al., 2021), with design guidelines fully described by Wallace et al. (2026). As CSOs are more concentrated than rainwater, it makes their treatment more challenging, especially when precise discharge limits have to be guaranteed by local authorities. In order to achieve these objectives, the design of the system has to ensure compliance with the targeted effluent quality, despite the unpredictable hydraulic loads and inflow concentrations.

In passive vertical CSO wetlands, the hydraulic design of the filter is achieved through a hydraulic simulation of the treatment chain. A mass balance is made between the volumes overflowing to the filter, draining through the filter, accumulating at the top (and inside) and possibly bypassing the filter. It enables the calculation of storage capacity and filter surface area, while respecting the annual maximal load constraint. A similar approach have been adopted for hydraulic design with aerated vertical CSO wetlands.

In order to guarantee that performance objectives are met, different approaches are proposed in the international guidelines for passive vertical CSO wetlands (Wallace et al., 2026). For instance, in the German approach, once the surface area and storage volume have been defined in accordance with hydraulic considerations, a check of the fine particles load and an estimate of the outflow concentrations based on assumed performances is carried out. Consequently, the removal performance of the filter itself does not impact design considerations. It is assumed that such performances will be attained in any case, provided that the design and filter media guidelines are respected, as well as operation is conducted properly. The French approach differs in that the hydraulic design is not defined separately from the removal objectives. This is due to the links between hydraulic and treatment processes. A dynamic tool has been developed to optimize the design based on a simulation of hydraulic and removal processes (Palfy et al., 2018). This tool allows for the consideration of potential ammonia storage and nitrate release during successive events.

In aerated vertical wetlands, aeration allows the aerobic condition to be maintained throughout the event, even if the filter is saturated. In this manner, the process of nitrification can be guaranteed during events that significantly reduce nitrate flushes. Consequently, it is possible to maintain low outflow nitrate concentrations. For these reasons, the design approach differs from that of a passive aeration system. Internationally, the feedback on aerated vertical CSO wetlands remains limited (Portela et al. (2024); Bresciani et al., (2026)).

The purpose of this guideline is to summarize the first proposed rules based on fully monitored systems under the NICE and Multisource H2020 European projects. Nevertheless, there are common principles that apply to passive system design. When recommendations are similar to passive systems, the reader will be advised to refer to Wallace et al. (2026) as this book provides comprehensive guidance on the design principles of passive systems.

The configuration of aerated CSO vertical TWs is similar to that of vertical TW used for domestic WW (see Wallace et al., 2026 for detail). The process utilizes saturated flow, with compressed air injected into the wetland bed to enhance oxygen transfer. In a similar manner to passive CSO vertical flow, they incorporate a regulated outflow rate to guarantee a precise hydraulic retention time, as well as a hydraulic buffer capacity. The filter consists of a deep, constantly saturated layer (typically 1.0 to 2.0 m) and a small, unsaturated layer at the top (typically 0.2 m) as illustrated in Figure 2.4.1.

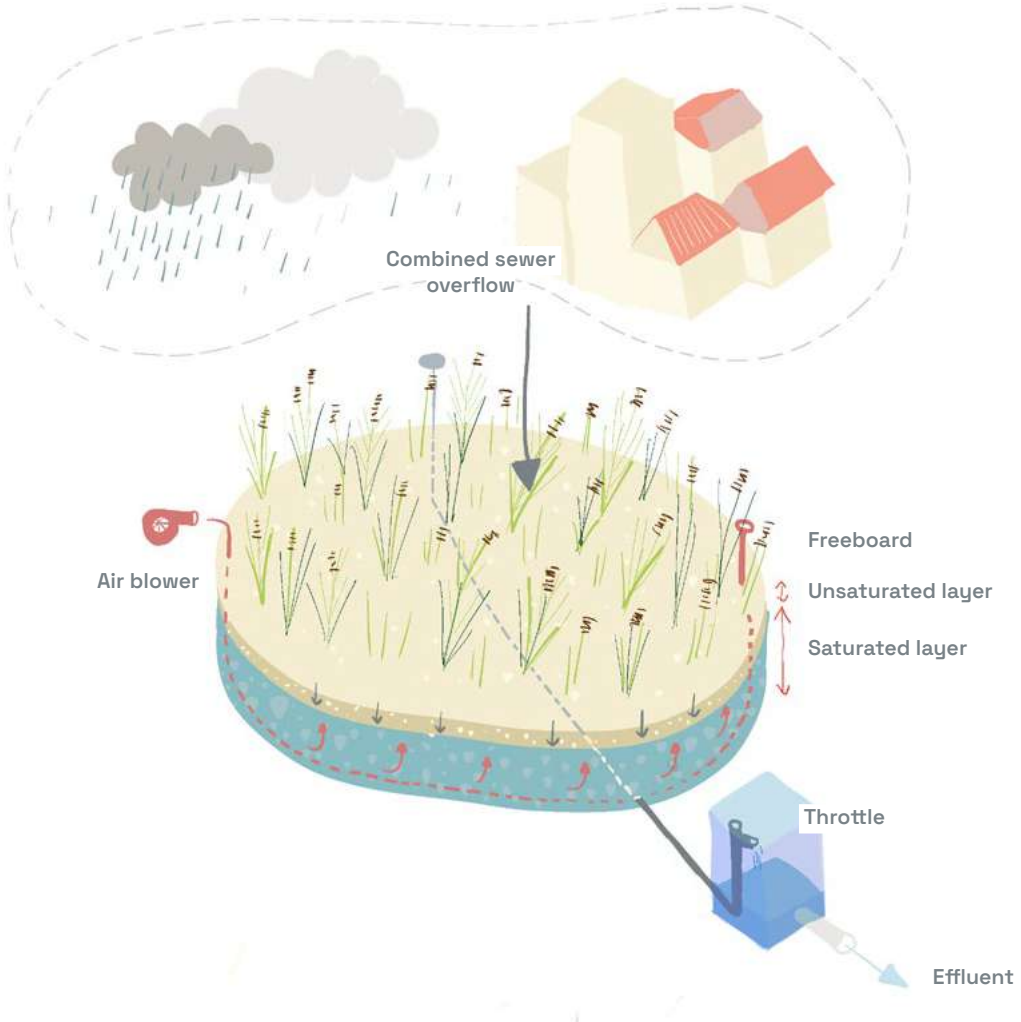


Figure 2.4.1

Typical representation of an aerated vertical flow treatment wetland for CSO.

2.4.2 Required data before designing a project

This section will specify the data and information that are needed to design a vertical flow treatment wetland for CSO.

The sizing of vertical CSO wetlands is complicated by the stochastic nature of overflows. One of the primary errors in the design of facilities and in reaching compliance with discharge levels arise from inadequate or imprecise knowledge of the behavior of the sewerage network in wet weather. Therefore, determining overflow events is a necessary preliminary step before sizing the treatment chain. Wallace et al. (2026) describe a methodology that can be used to determine overflows series over a long period, as well as to estimate pollutant concentration ranges that can be used for designing CSO wetlands. Acquiring accurate data is time-consuming, but essential for optimizing the design and consists of:

- Flow measurements at the overflow structure or within the sewer, and raingauge measurements, to fit a sewer model that can be used with confidence to simulate long-term series of overflows. In practice, this involves measuring more than 10 significant rainfall events across several seasons.
- Sampling measurements in the sewer for different rain events to ascertain the extent of variations in concentrations as a function of the discharge rate. It is challenging to establish correlations between concentrations and discharges. At best, it will be possible to establish trends that will allow hypotheses to be made about concentrations to be tested for sizing. In view of the variations that have been observed, it may be appropriate to modify the correlation in order to take these variations into account. The following pollutants can be monitored: COD, TSS, BOD and Total Kjeldahl Nitrogen (TKN). It is possible to monitor other pollutants too, but they are often not considered in the design of the TW.
- Establish a sewer model that can reproduce discharges during rainy weather, based on the rainfall/flow measurements taken. There are several software programs on the market that are able to simulate the hydraulics of sewers.
- Use a recent local rainfall record in the calibrated model to reproduce a series of overflow events, which will then be used for sizing. It is imperative that this rainfall record is of a duration that is equal to or greater than the rainfall return period targeted in the sizing. In order to take into account the impact of global warming, a future rainfall record can be used as well.

Further data is required CSO aerated TW design. This additional information relates to the contextual aspects of the site, including:

- The outflow concentration targets set by local authorities.
- The rainfall return period for which the design is intended.
- The available surface area and geotechnical soil constraints.

2.4.3 Design

The sizing of the filter surface area and storage volume is an iterative step that must be performed first. A dynamic simulation should be performed over a short time interval (generally a few minutes, in line with the time interval of the rainfall used to simulate overflows) in order to calculate the water balance between overflows entering into the system, drained flows, and the volume stored in the treatment facility. This approach does not take into account evapotranspiration, as it is considered as negligible. The water balance at each time step is based on the overflow data series from the sewer simulation and the outflow of the CSO treatment wetlands. The difference between these two data sets allows us to calculate the water stored in the treatment facility and, by extension, the water that has accumulated on top of the filter.

The calculation of controlled outflow rates is based on the relationship between the difference in ponding height at each time step and the height of the outlet orifice. The diameter of the outlet orifice is also a factor in the calculation. For that, the continuity equation and Torricelli formula can be applied for the estimation of the head loss. This formula is expressed as:

$$Q_{reg} = C_d \cdot S\sqrt{2gh_f}$$

where:

Qreg = regulated outflow, m^3/s

Cd = discharge coefficient (unitless, varying from 0 to 1), representing the ratio of the actual discharge to the ideal discharge through the orifice.

S = cross-sectional area of the orifice (m^2), corresponding to $S=\pi \times D2/4$, with D as the orifice diameter (m)

g = acceleration due to gravity (9.81 m/s2).

hf = head loss (m), in this case representing the difference in water level above the filter and the orifice level.

The discharge coefficient Cd varies with the type of flow and the geometry of the opening - typical values for various configurations are presented in hydraulic textbooks, but in the present case, they are likely to be between 0.65 and 0.90. In the case of a sharp-edged orifice, the jet undergoes significant contraction at the outlet, which reduces the effective cross-sectional area. The value of the Cd coefficient is thus found to be in the range of 0.6 to 0.65 for a circular orifice. In the case of a rounded-edge orifice, pressure losses are minimized and the coefficient value approaches 0.9.

In the case of pump drainage, the pump flow rate can be taken into account when calculating the outflow rate.

The water balance simulation enables the adjustment of both the filter surface area and the storage volume, with the objective of retaining the targeted design rainfall. In order to accomplish this objective, it is necessary to consider several criteria to ascertain the filter characteristics:

- The annual hydraulic load is estimated to range between 15 and 100 m/year. In instances where annual design loads exceed 50 m/year, it is advisable to divide the surface into two parallel filters. This approach is recommended to encourage mineralization of the organic deposit. Filters are systematically alternated on a monthly basis. This approach ensures that for smaller events, only a single filter is utilized, while for larger events, both filters can be employed simultaneously via an overflow from one to the other. Further details on parallel filter implementation can be found in Wallace et al. (2026).
- The maximum ponding height is limited to 2 meters.
- The drainage rate of the filter is between 0.01 and 0.05 liters per square meter of filter and per second.
- The event is completed within 48 hours.

It should be noted that the filter surface area may not allow the entire design volume to be stored for a ponding height of 2 m. In such cases, it may be decided to create gently sloping banks to increase the storage surface area without enlarging the filter surface area, in order to minimize construction costs. Whilst the land footprint has increased, the size of the filter remains unchanged.

Following the determination of the filter surface area, it is essential to verify that the annual suspended solids load remains within acceptable limits to prevent any long-term filter clogging. In passive systems, the German approach suggests that fine SS (less than 0.63 µm) are more prone to clogging (Wallace et al., 2026). They propose setting an area loading rate limit at 7 kg/m^2·y (DWA, 2019). In an aerated system, the filter material is larger, allowing SS to enter deeper into the filter and be distributed over a larger volume. As the filtration system is still operating efficiently, it is recommended that all SS is utilized to calculate the load, with a limit set at 15 kg SS/m^2/y. SS originates from domestic wastewater and particles washed off impervious surfaces that enter the sewer. Assessing these factors can be challenging and depends on the type of surface and its intended use. It is challenging to quantify them without taking samples. For this reason, it is recommended that sampling campaigns be carried out to estimate variations in SS concentrations according to the types of overflows. If it is possible to correlate concentrations and overflow volume, the correlation can be used on the overflow data series to estimate the annual load. If this is not feasible, average values can be tested on the overflow data series to determine whether the selected surface is safe in terms of SS load or close to the limit, and to adjust the surface accordingly.

Determining the filter's material

It is imperative to consider the parameters of media particle size and depth to ensure the effective operation of the system. It is evident that the particle size distribution of the filtration layers exerts a substantial influence on the performance of the system. In the context of CSO aerated TWs, a range of objectives is pursued with regard to the distribution of particle size across the various layers.

Initially, as the filter is fed with raw CSO (no primary treatment), the objective is for an organic deposit to form at the filter's surface, as is the case in French vertical flow TW for domestic wastewater (Molle, 2014). The use of sand at the filter's surface enhances filtration processes and promotes the formation of a deposit layer. However, it should be noted that this will create a physical barrier for air bubbles, which will have a detrimental effect on air distribution and oxygen transfer within the filter. Consequently, the use of a 2 - 6 mm gravel size is advocated to facilitate the formation of an organic deposit, whilst concurrently ensuring the preservation of optimal air permeability.

Secondly, in order to minimize internal clogging of the filter by fine solid entrapment and biomass accumulation over time, the saturated layer is composed of a 10 - 20 mm gravel layer. It has been demonstrated that it enables effective water mixing within the filter due to aeration. Indeed, Portela et al. (2024) demonstrated the mixing effect of aeration with such particle size. It allows decreasing possible hydraulic shortcuts and thus ensures consistent and reliable treatment performance.

The depth of the filter layers is also a key factor in filter performance. The purpose of the surface layer is twofold: firstly, to promote water distribution at the start of an event; and secondly, to retain the coarsest particles on the surface to form an organic deposit layer. In this regard, it is essential that the material does not have a too small thickness that would hinder its ability to perform the required filtration functions. It is important to note that achieving a significant depth would not be beneficial in terms of filtration efficiency. Main solids retention takes place in the first centimeters. The saturated layer, with a larger grain size, must ensure a sufficient residence time to guarantee treatment efficiency, while promoting optimal oxygen transfer and minimizing potential hydraulic short circuits. Consequently, it is deeper than the surface layer.

There is a paucity of feedback comparing the performance of filters according to material depth (Portela, et al. 2024; Bresciani et al., 2024). Table 2.4.1 sets out the recommended depths for achieving optimum performance.

	Particle size (mm)	Depths (cm)
Unsaturated surface layer	2 to 6	20 to 40
Saturated layer	10 to 20	80 to 150

Table 2.4.1

Recommended depths and particle size for the filtration layers

Designing an aeration system

The purpose of sizing the aeration system is to ensure a sufficient supply of oxygen to oxidize organic matter and ensure nitrification during a rainy event. Please refer to Wallace et al. (2026) for detailed instructions on the sizing of aeration systems. Only the key points related to the treatment of CSO vertical flow TWs are presented here.

Oxygen demand calculation for aerobic treatment

Oxygen demand is calculated based on the BOD to be removed and the KN to be nitrified. Denitrification is not taken into account as it is generally limited due to a short retention time and a lack of carbon sources. As overflow events can often extend beyond the hydraulic retention time, it is essential to calculate the hourly oxygen demand based on the regulated flow rate. The aeration system must then supply the necessary amount of oxygen per hour. The hourly oxygen demand can then be calculated using the following formula.

$$O_{2dem} = (BOD + 4.6 \cdot KN) \cdot Q_{reg}$$

where:

O_2dem = hourly oxygen demand, g/h

BOD = Inlet BOD concentration, g/m^3

KN = Inlet Kjeldahl Nitrogen concentration, g/m^3

Qreg = regulated outflow, m^3/h

In practice, as outflow can vary according to ponding height and pollutant concentrations can vary according to inlet dilution, it is necessary to make different assumptions when calculating the maximum oxygen demand the system might face.

Highest ponding level

It is of importance that the blowers compensate for head losses due to water pressure above the emitters, as well as those losses resulting from the emitters and distribution piping (please refer to Wallace et al., 2026 for more information). One of the features of CSO vertical flow TWs is that the water pressure varies according to ponding height. Therefore, when conducting the hydraulic simulation step presented above, it is essential to consider the maximum water ponding height when calculating the head losses that the blowers must address.

The number of emitters, their spacing, and the length of distribution tubing are presented in Wallace et al. (2026).

Oxygen transfers

Oxygen transfer efficiency depends on different parameters such as air flow, particle size of the gravel, temperature and diffuser type and density. Consequently, it is relevant to use value based on relevant aerated wetland studies.

Aeration strategy

Portela et al. (2024) demonstrated the importance of initiating aeration concurrently with the commencement of the feeding event to ensure effective water mixing within the filter and to prevent hydraulic short circuiting. It has been determined that, given the inefficiency of denitrification due to a lack of carbon and a short hydraulic retention time, aeration fractionation is not necessary. Nevertheless, in order to facilitate energy savings, it is possible to halt the aeration process prior to the conclusion of the feeding event. In

practice, aeration should be stopped once the ponding volume during the drainage phase is equal to the storage water volume within the porosity of the permanent saturation layer. During the dry period, between two rain events, Portela et al. (2024) proposed to implement aeration two times a day for 10 minutes each time to ensure the continued activity of nitrifiers.

Check performances

As noted by Portela et al. (2024) and Bresciani et al. (2026), the performance of the TSS, COD, and BOD_5 removal processes is consistently high and reliable. The two studies, which used similar material layers and distribution pipe density, both demonstrated consistent removal performances of 85%, 89%, and 95% for COD, BOD, and TSS, respectively. This resulted in outflow concentrations below 10 mg/L for BOD_5 and TSS and below 40 mg/L for COD.

The efficiency of nitrification is contingent on the aeration strategy employed, the hydraulic retention time, and the duration of the dry period. With the optimal aeration strategy presented above, the hydraulic retention time is the only design parameter that can be adjusted to improve nitrification, as the length of the dry period is not predictable. However, for a fixed design flow, increasing hydraulic retention time by lowering the outflow rate means that the storage volume above the filter has to be increased. Consequently, the system's footprint is increased. Portela et al. (2024) and Bresciani et al. (2026) reported nitrification performances (based on NH4-N) of 70% and 66%, respectively, for a hydraulic retention time of approximately 7 – 8 hours. Portela's (2025) observations indicate that a hydraulic retention time of 7–8 hours results in a nitrification reduction limitation of approximately 10 mg NH4-N/L.

The assessment of whether the outflow concentrations will meet the targeted ones can be conducted using removal performances observed on aerated wetlands, as demonstrated by proper design and operation, as well as ammonia concentration reduction limitation (see Table 2.4.2). Should the ammonia outflow concentration not reach the target concentration, the hydraulic retention time can be increased. Another option that should be considered is to validate the use of a small amount of wastewater during dry periods to increase nitrifying bacteria within the system. This would make the system more efficient during rain events.

	COD	BOD_5	TSS	$N\text{-}NH_4^+$
Removal performances (%)	85	89	95	65 (10*)
Ammonia concentration reduction (mg/L)				10

**ammonia concentration (mg/l)*

Table 2.4.2

Average performances removal rate and ammonia concentration reduction to be used to check estimate outflow concentrations.

2.4.4 Design example

The example illustrates the design of an aerated CSO vertical filter to treat an average annual volume of 32,000 m³/year and, as an extreme event, a 24-hour flow of 3,055 m³ corresponding to an annual return period event. Figure 2.4.2 represents the annual overflow data series that is used for design (time step 5 minutes). The following effluent requirements must be met: 90 mg/L of COD, 25 mg/L of BOD_5, 30 mg/L of TSS and 15 mg/L of TKN.

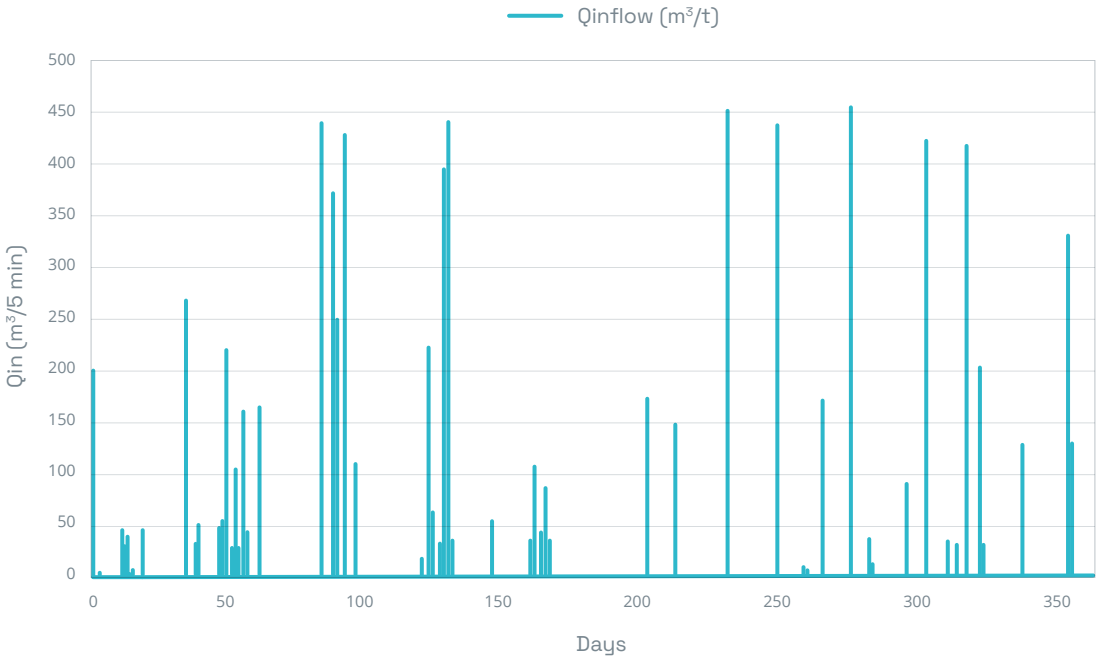


Figure 2.4.2

Annual overflow data series used for design.

Hydraulic design

A maximal annual hydraulic load of 50 m/year was defined. Consequently, the filter's surface is:

$$S_{filter} = \frac{Annual\ volume\ (m^3)}{Annual\ maximal\ load\ (\frac{m^3}{m^2})} = \frac{32{,}000}{50} = 640\ m^2$$

To assess whether the proposed surface meets the hydraulic rules, it is necessary to run a dynamic hydraulic simulation. It will allow adjustment of the regulated outflow and the storage volume. The criteria to verify are:

- The annual hydraulic load is estimated to range between 15 and 100 m/year (proposed at 50m/y in first assumption).
- The maximum ponding height is limited to 2 meters.
- The drainage rate of the filter is between 0.01 and 0.05 liters per square meter of filter and per second.

The event is completed within 48 hours.

The water balance simulation can be performed using a standard spreadsheet program. This will allow the outflow rate and the ponding height over time to be defined. The diameter outflow orifice can be adjusted for this purpose. The outflow is calculated according to the following formula:

$$Q_{reg} = C_d \cdot S\sqrt{2gh_f}$$

It is assumed that the discharge coefficient, Cd, is 0.8 in this instance. The calculation results, for an orifice diameter of 8 cm, are presented in Figure 2.4.3.

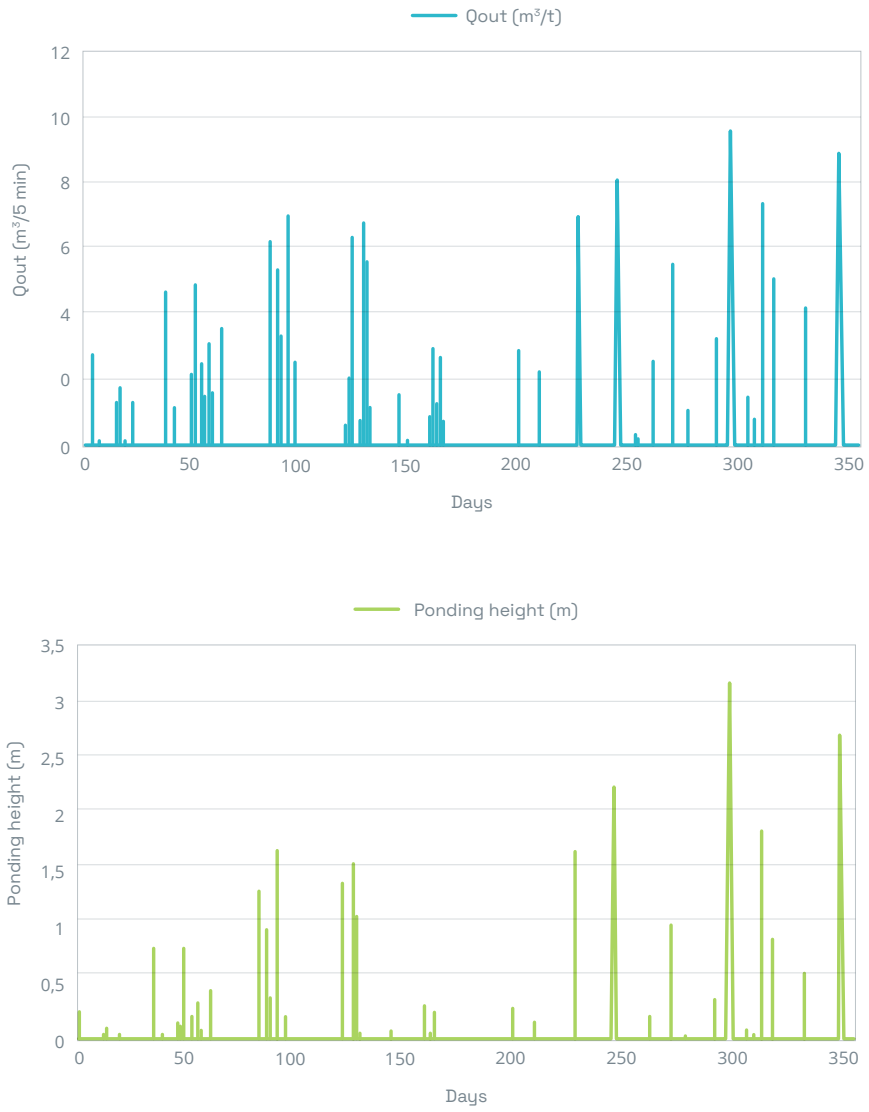


Figure 2.4.3

Outflow rate (left) and ponding height simulated.

According to the simulation, it is possible to define the maximum outflow rate. The outflow rate is 0.05 liters per square meter per second, which is in accordance with the design criteria. Regarding ponding height, it is possible to define the volume to be stored (maximum ponding height multiplied by the filter's surface). It is 2,086 m^3. The ponding height simulation indicates that the maximum ponding height exceeds the 2 m criteria for three rain events. Therefore, it is necessary to modify and adapt the design in order to reduce the maximum ponding height. It has been determined that increasing the office diameter is not a viable option. The maximal outflow rate has already been set at 0.05 liters per square meter and per second. Two options are available for consideration: increasing the filter's surface or implementing low-slope banks to increase storage capacity without increasing the filter area. Increasing the filter surface will result in higher investment costs (more materials, aeration pipes, and more powerful blowers). The decision has therefore been taken to increase the storage surface by implementing low-slope banks. In order to ensure that the maximum ponding height does not exceed 2 meters, the storage surface area should be calculated at 2,086/2= 1,043 m^2.

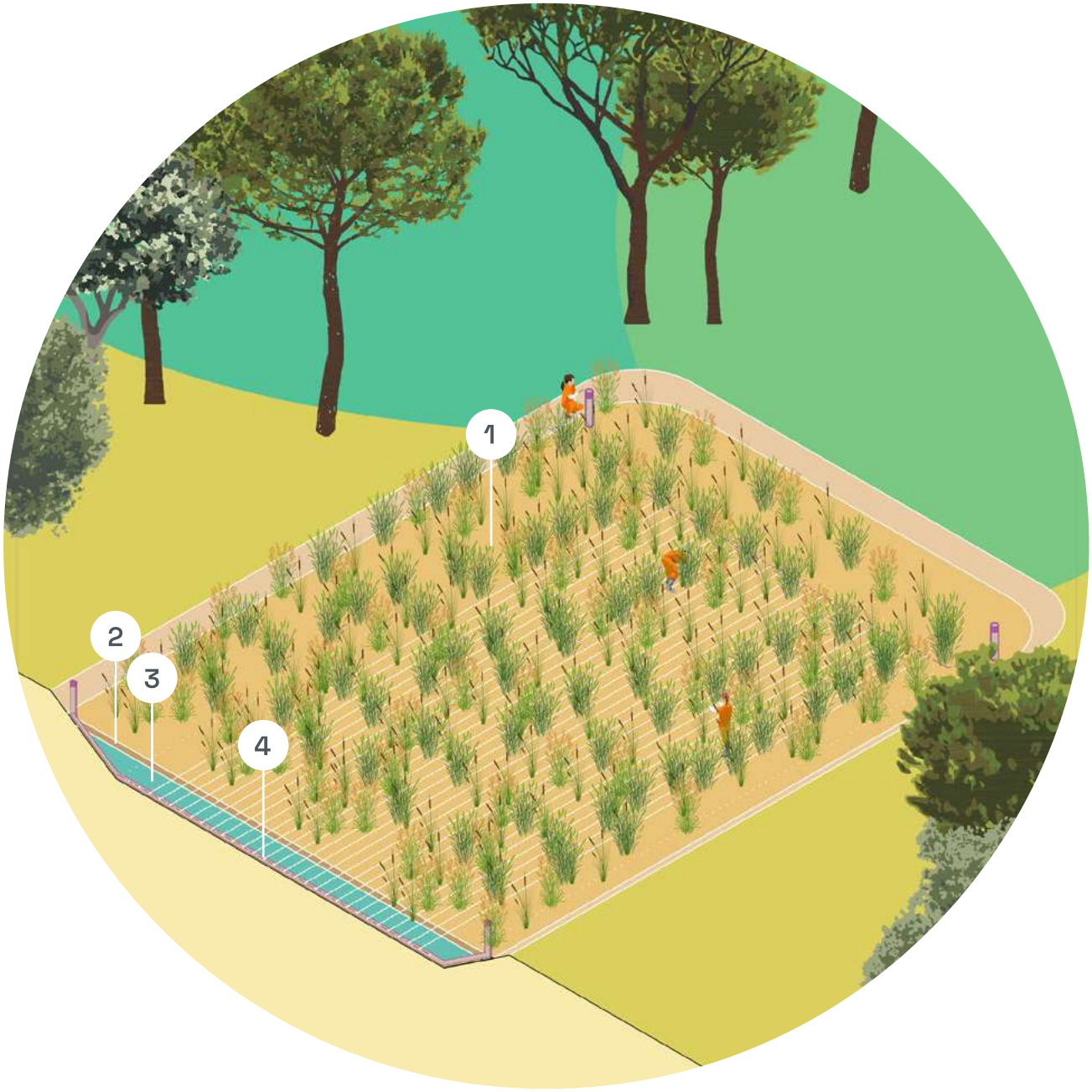
The final criterion to be checked relates to the maximum drainage time (48 hours), which can be easily verified by the simulation. This is the case in the present design example.

The hydraulic design can be summarized in Table 2.4.3.

Table 2.4.3

Design parameters from hydraulic simulation.

Design parameters	Filter surface area	Storage volume	Storage surface area	Maximum ponding height	Orifice diameter
	640 m^2	2,086m^2	1,043 m^2	2 m	8 cm



1. Freeboard
2. Unsaturated layer
3. Saturated layer
4. Air ventilation system





Filtration layers composition

Filtration layers are set according to Table 2.4.1:

- An unsaturated filtering layer over 40 cm, made of filtration gravels (2-4 mm)
- 100 cm of saturated coarser gravels (10-20 mm) in which are located drainage pipes and the aeration network connected to the blowers.

Checking the compliance of outflow concentrations

In order to verify the compliance of outflow concentrations, it is necessary to refer to the removal performances indicated in Table 2.4.2. For this, inflow concentrations must be defined with the greatest possible precision. It is important to note that local regulations stipulate the need to meet outflow concentration requirements in a specified percentage of cases. For instance, these requirements must be met on average or in 95% of cases. Consequently, having access to information regarding inlet concentration variations is essential. In Table 2.4.4, is presented the hypothesis of inlet concentrations that will be used in the design example. It is possible to set those concentrations using a literature review of similar catchment areas, or – ideally – existing data on the combined sewerage system during rain events (for example, at the entrance to the wastewater treatment plant).

During overflow events, flow and concentrations can vary significantly. For this reason, the design is based on the event mean concentrations. Obtaining quality data can often be challenging prior to designing a treatment system. Should there be a trend indicating a decrease in event mean concentrations alongside increasing overflow volumes, a high degree of variation is to be expected, and it is generally not possible to establish a perfect correlation. Consequently, a hypothesis must be formulated in terms of design event mean concentrations to estimate outflow concentrations and to design aeration equipment. It is not usually necessary to design the system for the maximal concentrations and flow, as this would overestimate outflow concentrations and oversize the aeration equipment. In this example, the 75th percentile is utilized. However, the designer has the option to formulate alternative hypotheses to assess the robustness of the system under design. Please refer to Table 2.4.4 for details of the results. TN and TP are presented as information since the design is not done for P removal and denitrification.

Parameters	CSO Inlet concentrations Range (95% interval)	CSO Inlet concentrations (median)	Design inlet concentrations (75th percentile)	Design inlet loads based on the maximal overflow event of the data series and design inlet concentration
	mg/L	mg/L	mg/L	kg/h
TSS	50–550	200	260	32.5
COD	120–450	190	300	37.5
BOD_5	30–230	70	100	12.5
TKN	1–30	7	12	1.5
NH_4-N	1–28	6	11	1.38
TN	1–30	7	12	1.5
TP	0.5–11	2	5	0.62

Table 2.4.4

Event mean inlet observed and design concentrations and design loads.

Applying the removal performance data from Table 1 to the design inlet concentrations results in the following estimated outflow concentrations: 45 mg COD/L, 11 mg BOD_5/L, 13 mg/ TSS/L and 4.2 mg N-NH4+/L. When using a maximum of 10 mg/l of ammonia concentration reduction, the outflow ammonia concentration would reach 1 mg/L. Consequently, the outflow concentrations meet the target concentrations in all conditions. This validates the use of the CSO aerated vertical flow filter in such application.

Design of the aeration system

The estimation of the oxygen demand is based on the BOD_5 and NH4-N influent mass loadings. It is calculated on an hourly basis. Using the highest outflow rate of 0.05L per m^2 and per second (115.2 m^3/h with 640 m^2 of filter), the oxygen demand is therefore:

$$O_{2dem} = (BOD + 4.6 \cdot TKN) \cdot Q_{reg} = (100 + 4.6*12)*$$ 115.2 = 17,879 g/h = 17.879 kg/h

Taking this oxygen demand into account, the airflow can be calculated using the following data: the air contains 23.1% oxygen by mass under Earth-standard conditions and a load and the standard oxygen transfer efficiency (SOTE). The standard oxygen transfer efficiency (SOTE) ranges from 4.7% per m to >30% per m of water depth submergence (Wallace et al., 2026). In this example, we will consider a SOTE of 8 %. As well, it is considered that elevation and average temperature of the site lead to an air density (ρair) of 1.16 kg/m^3. The air flow can be calculated as:

$$Q_{air} = \frac{Oxygen\ demand}{C_{air} * SOTE * \rho_{air}} = \frac{17.879}{0.231 * 0.08 * 1.16} = 834\ m^3/h$$

The real air flow necessary needs to consider head losses due to the hydrostatic (water) pressure with the maximum ponding height, the air pressure required by the emitters, and minor frictional losses that occur in the air distribution system.

The air network located at the bottom of the filter and connected to low-pressure blowers, must be sized to provide an air flow rate of 843 Nm^3/h, homogeneously distributed across the surface. Figure 2.4.4 presents an example of the air distribution system.

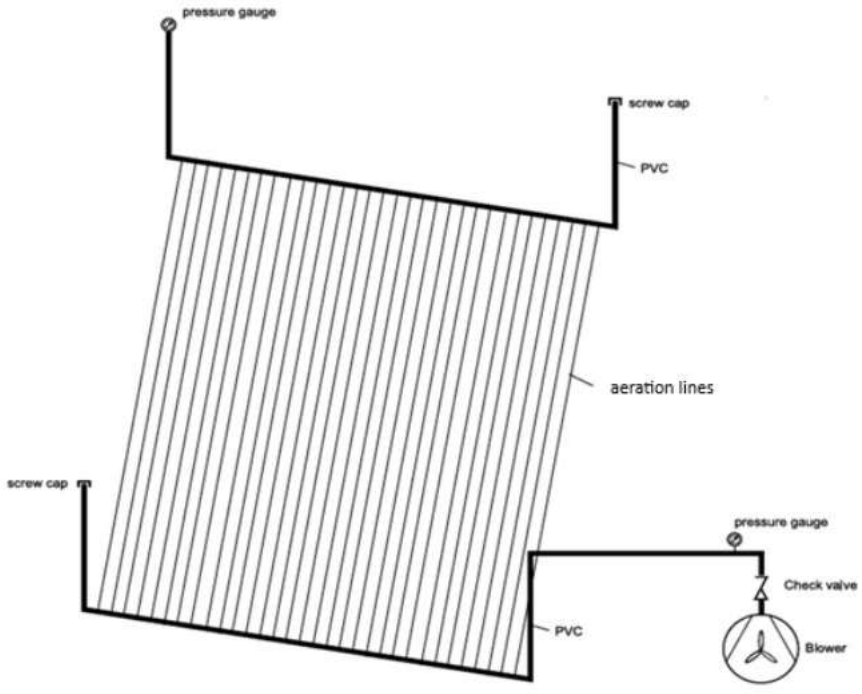


Figure 2.4.4

Aeration network layout and blower connection.

2.4.5 Implementation

The implementation of an aerated vertical flow TW for CSO involves several key steps, including site evaluation and selection, specific elements to consider in the implementation (malfunctioning; operation and maintenance aspects; monitoring; construction phase; health, safety and environmental factors ...); plant layout, hydraulic profile, and technical drawings that are common for all TW technologies. These main phases and recommendations are presented in Wallace et al. (2026). This section outlines key considerations when managing CSO treatment.

Given that CSO TWs may be established in peri-urban areas where land pressure is significant, it is important that the area surrounding the filter provides sufficient space for machinery operation, such as surface deposit removal. Filter design must also anticipate access requirements for targeted maintenance activities. The embankment slope affects accessibility to the filter interior; a minimum slope of 1:1 is standard, but a gentler slope can enhance storage capacity and facilitate access. Where land constraints are pronounced, filter sides may be constructed using gabion walls with applied liners (see Wallace et al. 2026); in these instances, dedicated access points for maintenance and operational activities should be incorporated.

Elevation and grading

This process involves the fundamental earthwork activities involved in the excavation and grading of TWs. One of the particularities of CSO TWs is that inflows vary considerably according to the intensity of rainfall. Consequently, it is not feasible to design a pumping station that can effectively manage these inflow variations in real time. It is therefore strongly advised that a detailed topographic survey be conducted in order to implement a hydraulic profile that can ensure gravity-driven feeding. In instances where the site does not permit a full gravity-driven profile, pumping becomes essential. In that case, it would be advisable to install a pumping step at the outlet, as the outflow must be regulated. The outflow is small and stable, so pumps can regulate it. In instances where topography does not permit gravity-fed feeding, the use of pumping systems becomes essential. It is therefore recommended that a buffer capacity tank be implemented in order to face inflow variations and lower the pump capacity.

Filter implementation

All TWs systems share the same implementation tasks, which include earthworks, waterproofing, drains and filtering aggregates filling for example. For a comprehensive overview of these aspects, please refer to the publication by Wallace et al. (2026). The distinctive features of aerated CSO vertical flow treatment wetlands are associated with the inflow and outflow structures, as well as the aeration system.

- **Aeration system**

  The aeration system must be carefully installed at the bottom of the filter before filling the system with gravel layers. Once the aeration tubing has been covered by the full depth of the wetland bed media, it is difficult and expensive to excavate and fix connection problems that could have been easily corrected earlier in the construction sequence. As a result, most wetland practitioners will test the aeration system with only a shallow layer of gravel (to hold the aeration tubing down), flooding the bed, and visually observing the air bubble pattern with the construction contractor (see Figure 1.4.5).



Figure 1.4.5

Aeration network implementation (left) and aeration network testing (right). With the courtesy of EcoBIRD.

Aeration must be scheduled in sequences of aeration and non-aeration. It is important to note that these sequences differ during periods of rain and dry weather. Consequently, aeration must be controlled by an automaton. Aeration during the dry period can be managed by implementing a timed programme (for example, two 10-minute periods of aeration per day). However, it should be noted that this is not applicable in feeding events. Aeration must commence at the start of a feeding event and cease during the drainage phase once the ponded water volume equals the permanent water volume of the filter porosity. To achieve this, it is possible to regulate aeration in accordance with the dynamic of the water level stored in the filter.

- **Inlet flow distribution**

All performances presented in this guideline refer to systems that have been evaluated with a similar design. In addition to the media size and layer, the distribution of water at the top surface is a key feature to consider. It is evident that the distribution of water across a vertical filter has a significant impact on the potential for hydraulic shortcuts and, consequently, on performance. Both studies from Portela et al. (2024) and Bresciani et al. (2026) used a feeding point density of one point per 20 or 25 per m^2 of filter. The distribution point density, which utilised below-ground distribution pipes with a riser pipe at the feeding point, was employed by pumping CSO to the filter. When the filter is fed by gravity, it is necessary to implement above-ground feeding pipes. In such cases, the presence of a high linear pipe above the filter can present certain maintenance challenges, particularly during the emptying of the organic deposit layer after 15 to 20 years of operation. Consequently, using a lower feeding point density, as employed in passive vertical flow treatment wetlands (see Wallace et al., 2026), can appear attractive. It should be

noted that decreasing the feeding point density may be possible while maintaining removal performances presented in this guideline for three main reasons. Firstly, the 1 m permanent saturation level significantly reduces hydraulic shortcuts. Secondly, setting aeration at the start of a feeding event ensures vertical water mixing in the reactor. Finally, during a rain event, the outflow is considerably lower than the inflow. This results in the rapid appearance of water ponding, which favours its distribution at the top. It is therefore realistic to envisage a distribution system similar to that implemented in passive vertical flow CSO treatment wetlands without altering treatment performances.

- **Outflow regulation**

The drainage configuration aligns with that of other vertical flow TWs. For detailed guidance on designing drainage pipes, readers are referred to Wallace et al. (2026).
In vertical flow CSO wetlands, various methods can be employed to regulate outflow rates:

  - *A manual valve installed in the main outlet drainage pipe enables the outflow rate to be set and adjusted; once established at the required value, changes are typically infrequent.*
  - *Alternatively, a calibrated orifice may be fitted for water discharge. Should adjustments to the outflow rate be necessary, the existing orifice must be manually replaced with one of different dimensions.*
  - *Where gravity-driven operation is impractical due to insufficient elevation differences between the inlet and outlet, pumping becomes essential. Outflow can be maintained by a pump at a consistent and low rate at the outlet.*

Commissioning – initial inspection, water flow testing, and adjustments.

The commissioning process includes hydraulic testing to verify the performance of each hydraulic structure or pumping system, ensuring uniform water distribution and retention time. Initial inlet and outlet water quality sampling is conducted to confirm treatment performance. It may be necessary to make adjustments to the aeration patterns (air flow rate, aeration duration and sequencing) in order to optimize efficiency. This phase also includes operator training on routine maintenance and documentation of system performance. Proper commissioning is essential for ensuring long-term reliability and compliance with company standards.

2.4.6 Management, operation and maintenance

As with any TWs and wastewater treatment plants in general, CSO vertical flow wetlands require proper operation to ensure the system's performance and longevity. Although TWs are known to require less maintenance than grey infrastructures, they still require systematic care to avoid performance decline. Nevertheless, when compared with grey infrastructure for managing CSOs, TWs appear to be a very attractive economic option over the systems' lifespans (Lipera et al., 2025). The management and operation of CSO aerated vertical flow wetlands have some specific features compared to other TWs. These are presented in three categories below.

VEGETATION MANAGEMENT

Due to a high permanent saturated zone, contrary to passive CSO vertical filters, plants are not prone to suffering from water stress. However, when hydraulic loads are low, potential competition from invasive species should be considered, according to the depth of the top unsaturated layer. It is imperative that non-aquatic vegetation, especially woody plants, is removed promptly to prevent structural damage to the filter media. In contrast to many other TWs systems, plants in CSO wetlands are not harvested. Their natural die-back during winter promotes the rapid formation of organic deposits, which contribute to improved water distribution across the filter surface and enhanced pollutant adsorption.

ROUTINE OPERATION

It is critical to verify that all parts of the treatment system are operating effectively. This includes tasks associated with mechanical and physical equipment, as well as ensuring the proper hydraulic performance of filters, particularly in addressing issues such as clogging. Consistent monitoring of the inlet (overflow weir, screening, sedimentation tank if present, gabions) and outlet structures (throttle, standpipe) should be performed monthly, with additional inspections following significant rainfall events. Any necessary adjustments, maintenance, or repairs to throttles and related mechanical equipment must be addressed promptly upon detection of an issue. Hydraulic assessments should utilize basic monitoring equipment. Flowmeters are valuable not only for regulation but also for understanding the hydraulic load experienced by the filter. Operators are responsible for conducting monthly checks on all hydraulic components—from inlet to outlet—to detect and address potential blockages or damages affecting filter and monitoring system functioning. Operators are required to calibrate all pumps, flowmeters, and throttle outflow rates annually to ensure optimal performance. With regard to blowers and aeration systems, it is essential to check the air pressure during aeration on a monthly basis. This will ensure that no clogging occurs in the aeration pipe. Blowers must be fitted with new air filters every two years.

MANAGEMENT OF ORGANIC DEPOSIT

The accumulation rate of sludge deposits on the surface of CSO wetlands is not comprehensively documented in existing literature. Nevertheless, once deposit thickness surpasses a certain threshold, it can negatively impact both infiltration and the ability of air bubbles to pass the organic deposit. The progression of deposit build-up is influenced by the solids load delivered to the filters as well as the characteristics of those solids, whether mineral or organic in nature. Accumulation patterns may vary spatially depending on inflow distribution. Regardless of the vertical CSO system design, periodic removal of accumulated deposits is unavoidable. While the exact interval for removal is not clearly defined, it is typically estimated to fall within a range of 10 to 20 years of operation.

Frequency	Location	Tasks
As needed	Filter	During the first year, remove non-aquatic vegetation, especially woody plants. Cut any woody plants growing on the filter.
Monthly	Filter surface / Inlet pipes (if gravity feeding without screening)	Once the basin is dry, remove any large waste accumulated and dispose of it.
Monthly	Filter	Verify that all physical and mechanical equipment and the proper hydraulic performance are operating effectively.
Once every two to three years	Blowers	Change the air filter on the blowers.
10 to 20 years of operation	Filter cleaning / Accumulated sludge excavation	Cut the reeds and remove the mineralised sludge from the surface of the filter bed. The process of removing sludge and recycling it in agriculture involves adhering to the current regulations that govern the spreading of sludge in agricultural contexts.
In the event of accidental pollution	Water level control and containment manhole	Close the manual valve in order to contain pollution in the basin (accidental spills, fire water, etc.) and implement a specific cleaning and disposal procedure according to the nature of the pollution.

Table 2.4.5

Routine maintenance tasks

2.4.7 Alignment with the IUCN global standards

Nature-based Solutions (NbS) developed within the NICE project aim to deliver not only effective technical performance, but also broader environmental, social, and governance benefits. The IUCN Global Standard for Nature-based Solutions provides an internationally recognised framework for designing, assessing, and scaling NbS, ensuring that such interventions effectively address societal challenges while maintaining ecosystem integrity, economic feasibility, and long-term sustainability.

This section evaluates how the presented NbS typology and its implementation in the NICE Urban Real Labs (URLs) align with the eight criteria of the IUCN Global Standard. The assessment identifies current strengths, highlights aspects that may require further development, and proposes actions that could strengthen compliance with the Standard.

Table 2.4.6 presents the alignment assessment for the Lyon NICE URL, summarising the status of each IUCN criterion together with supporting commentary and recommended actions to improve alignment. Building on this case-specific analysis, Table 2.4.7 outlines general considerations for the alignment of Vertical Flow Treatment Wetlands for CSO management with the IUCN Global Standard. These considerations are intended to support the design, implementation, monitoring, and replication of this NbS typology in other urban contexts.

Together, the assessment and derived recommendations provide a structured basis for ensuring that the proposed solution contributes to sustainable urban water management while supporting policy integration, adaptive management, and long-term mainstreaming of NbS approaches.

IUCN criterion	Status	Commentary	Actions to fulfil or strengthen alignment
C1. Address societal challenges	+	The pilot treats real stormwater and combined sewer overflows (CSO), preventing untreated discharges into the river. This preserves downstream water quality and supports recreational use for citizens.	Link specifically CSO treatment to societal outcomes such as public health protection, climate resilient sewage management and enhancement of water quality in surface water bodies.
C2. Design informed by scale	±	The pilot is designed to be scalable and adaptable to different contexts. Ongoing monitoring of pollutants provides data to inform upscaling, with larger systems planned for the Lyon metropolis to validate transferability.	Upscaling of the solution through replication and integration within the local sewage network.
C3. Net gain to biodiversity	±	By treating CSO and buffering hydraulic flows, the system reduces pollution impacts and riverbank erosion, enhancing habitat quality for fauna and plant species.	Integrate ecological design features, including native plant palettes, habitat structuring, and when possible connectivity with riparian corridors. Monitoring of biodiversity indicators alongside treatment performance.
C4. Economic viability	+	The system significantly reduces investment costs for CSO management compared to grey infrastructure solutions such as sewer capacity increases or storage basins. While ecosystem service valuation has not yet been conducted, existing literature suggests additional benefits.	Conduct a comparative cost–benefit analysis including avoided grey infrastructure costs, and quantifying ecosystem services.
C5. Inclusive governance	±	The system was co-designed between INRAE (research institution) and EcoBird (private company), rather than through citizen participation. However, the governance model leverages scientific and technical expertise.	Introduce structured stakeholder engagement mechanisms targeting municipalities, residents, river-user groups during planning and design of the NbS.
C6. Balance of trade-offs	±	Although primarily a research facility, the site attracts citizens due to its natural setting, generating public interest and dialogue around NbS. The main trade-off is between its research focus and its broader societal integration.	Analyse trade-offs across land-use and operation and maintenance responsibilities.
C7. Adaptive management	+	Performance monitoring and iterative adjustments ensure that the wetland continues to function effectively, applying adaptive management principles directly.	Expand monitoring to include long-term resilience indicators (performance during extreme rainfall, sediment accumulation, vegetation dynamics, climate stress response).
C8. Mainstreaming & sustainability	+	The pilot aligns closely with Lyon Metropolis policies on stormwater and river protection. Strategic communication targets municipal engineers, national decision-makers, and citizens visiting the site, supporting mainstreaming and long-term acceptance.	Embed the typology into urban stormwater masterplans, technical standards, and regulatory frameworks

Table 2.4.6 Alignment of the Lyon NICE URL with the eight criteria of the IUCN Global Standards

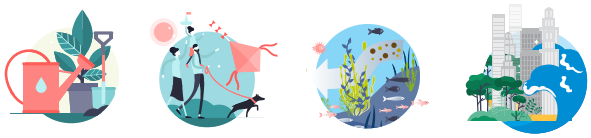
IUCN criterion	Considerations
C1. Address societal challenges	• *Clearly define the societal challenges addressed (urban water pollution, climate resilience, public health protection).* • *Link CSO mitigation outcomes to tangible co-benefits such as enhanced water quality in rivers and lakes, reduced flood risk, and reduced health risks.* • *Develop indicators that translate treatment performance into societal value*
	Main societal challenges addressed by this typology:  GREEN SPACE MANAGEMENT | HEALTH & WELL-BEING | WATER MANAGEMENT | NATURAL & CLIMATE HAZARDS
C2. Design informed by scale	• *Design systems to function across multiple rainfall scenarios, including extreme storm events expected under climate change.* • *Ensure modularity so wetlands can be replicated at multiple discharge points within a catchment.* • *Integrate the wetland into the broader sewer network*
C3. Net gain to biodiversity	• *Select native, flood-tolerant vegetation to create functional habitats while maintaining treatment efficiency.* • *Design substrate structure and hydrology to support microbial diversity and ecological niches.* • *Connect wetlands to existing blue-green corridors to avoid isolated systems* • *Monitor biodiversity outcomes alongside water quality.*
C4. Economic viability	• *Compare lifecycle costs with grey alternatives such as storage tanks, sewer enlargement, or advanced WWTP upgrades.* • *Account for avoided infrastructure investments, reduced energy use, and lower operational complexity.* • *Include valuation of ecosystem services (erosion control, carbon sequestration, urban cooling, amenity value).*
C5. Inclusive governance	• *Involve municipalities, water utilities, local communities, and river managers early in planning.* • *Use demonstration sites as educational and participatory spaces to build acceptance of NbS and their ability to address sanitation challenges.* • *Clarify institutional roles for ownership, maintenance, and monitoring across municipal departments (water, environment, public space).*
C6. Balance of trade-offs	• *Balance optimization for pollutant removal with landscape integration, accessibility, and ecological value.* • *Address land-use trade-offs, especially in dense urban environments where space competition is high.*

Table 2.4.7 Key Considerations for the Alignment of Vertical Flow Treatment Wetlands for CSO Management with the IUCN Global Standards

IUCN criterion	Considerations
C7. Adaptive management	• *Establish long-term monitoring frameworks including hydraulic performance, pollutant removal, vegetation health, and sediment accumulation.* • *Use data to refine operational strategies* • *Incorporate learning from extreme weather events to adjust design standards.* • *Combine technical monitoring with environmental indicators to demonstrate multifunctionality.* **Relevant indicators of NbS performance and impact to be considered for Vertical Flow Treatment Wetlands:** *Water management:* *3.2 Water quality:general urban* *3.3: Water quality: TSS content [mg/L]* *3.4: Nitrogen and phosphorus concentration or load [%]* *3.5: Metal concentration or load [%]* *3.6: Water quality: total faecal coliform bacteria content of NbS effluents [No.]* *4.4: Peak flow variation [%]* *4.8 Rainfall interception of NbS [mm/h]* *4.11: Rainfall storage capacity of NbS [mm/%]* **Evaluating the Impact of Nature-based Solutions: A Handbook for Practitioners (EC, 2021)*
C8. Mainstreaming & sustainability	• *Align with water-quality directives, urban resilience plans, and nature restoration policies to secure long-term institutional support.* • *Promote capacity-building for engineers and planners to integrate NbS into conventional drainage practice.*

2.4.8 References

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3.
SUBSTRATES AND ADSORBENT MEDIA FOR NATURE BASED SOLUTIONS

Nature-based solutions are a relatively recent concept, defined as systems inspired by nature and designed to address and mitigate a wide range of environmental, social, and economic challenges, while simultaneously providing benefits for human well-being and biodiversity. The effects of NbS include ecosystem restoration, climate change mitigation and adaptation, and the sustainable use of materials and energy. In general terms, NbS can be understood as green infrastructure that can replace, enhance, or function in parallel with the urban landscape in order to generate ecosystem benefits.

There is a wide range of NbS techniques and systems. Among the most well-known are treatment wetlands, green walls, green roofs, and rain gardens. All of these systems have a strong capacity to adapt to the impacts of climate change and to enhance local biodiversity. Furthermore, numerous studies have confirmed the effectiveness of these systems in water treatment. Considering that NbS mimic natural ecosystems and are essentially composed of substrates, bacteria, and plants, bioremediation and adsorption are key processes in the removal of pollutants from water. Therefore, substrates and filter media are recognized as crucial components for treatment performance. They also serve as structural support for plant growth and microbial development, directly influencing bioremediation processes and contributing to the prevention of clogging within these systems.

Consequently, numerous studies and reviews have been conducted to support the appropriate selection of substrates for NbS applications targeting the adsorption of different contaminants. According to Ji et al. (2022), based on material characteristics and origin, media substrates can be classified into traditional mineral materials, manufactured chemical products, biomass materials, industrial and municipal waste materials, modified functional materials, and novel materials (Table 3.1).

NbS Substrate Category	Characteristics	Examples
Mineral materials	Raw materials from natural sources are generally abundant, widely available, and low cost.	Gravel, sand, natural zeolites, soil, etc.
Chemical products	Manufactured from mineral materials or waste-derived materials.	Ceramics, synthetic zeolites, polystyrene foam, etc.
Biomass materials	Heterogeneous mixtures of organic and inorganic matter, including agricultural residues, wood and woody waste, animal and human waste, aquatic waste, domestic and industrial waste, and commercial residues. Generally abundant and low cost.	Shells (oyster, mussel, etc.), biochar, rice straw, reeds, etc.
Industrial and municipal waste materials	By-products from industrial activities and urban development; availability may vary.	Furnace slag, crushed bricks, drinking water treatment residues, sawdust, polyethylene waste, construction by-products, etc.
Modified functional and novel materials	Materials modified to enhance adsorption capacity or innovative materials showing adsorption potential.	Porous geopolymer, lightweight expanded clay aggregates, micro-sized polysiloxane/alumina composites, etc.

Table 3.1

Classification and examples of adsorbent substrates for use in Nature-based Solutions for water treatment (source: Ji et al. 2022).

Despite the extensive range of adsorbent materials available for use in NbS, selecting the most suitable substrate for a specific system is not straightforward. Multiple factors must be considered to ensure both efficiency and long-term functionality. Key criteria include:

- **material cost,**
- **source and availability,**
- **hydraulic and engineering feasibility,**
- **pollutant removal capacity,**
- **ability to support plant growth and microbial attachment,**
- **safety (including the risk of secondary contamination),**
- **susceptibility to clogging,**
- **substrate lifespan.**

However, in many cases, substrate selection is primarily driven by cost and local availability, often due to limited technical information regarding the performance and long-term behaviour of different materials. As a result, choosing a substrate based solely on these two factors may compromise system efficiency and long-term sustainability. Furthermore, given the variability in contaminant composition and concentration, as well as the specific conditions at each implementation site, not all materials are suitable for every application. Careful, context-specific evaluation is therefore essential to ensure optimal performance of NbS systems.

Building on the considerations discussed above, one of the emerging challenges in the application of NbS for water treatment is the effective removal of emerging contaminants. In this context, substrate selection becomes even more critical, as the physicochemical properties of the filter media can significantly influence the system's capacity to retain and degrade these compounds.

Many emerging pollutants exhibit hydrophobic characteristics or interact through electrostatic forces, which promote their adsorption onto soil particles and substrate surfaces. Consequently, the composition, surface area, porosity, charge, and grain size distribution of the filling material directly determine the treatment efficiency of the NbS configuration.

For this reason, careful selection and design of substrate materials are essential to enhance adsorption and support complementary biological degradation processes. Optimising these properties not only improves the removal of emerging contaminants but also contributes to the overall robustness, long-term performance, and adaptability of the system under varying operational conditions.

Within the framework of the NICE project, a bibliographic review was conducted to collect information on substrates used in NbS, focusing on media capable of adsorbing emerging contaminants (see Table in the annex). However, many studies have not evaluated the adsorption capacity of these materials for emerging contaminants. Therefore, through adsorption assays, characterization analyses, leachate testing, and laboratory-scale experiments, the NICE project identified two materials—coco coir and sludge-derived biochar—that effectively adsorb five emerging contaminants: diclofenac, azithromycin, imidacloprid, 17-β-estradiol, and estrone.



Biochar SS Coco coir

Figure 3.1

Selected substrates in the NICE project with notable adsorption capacities for emerging contaminants.

During the experimental period, lab-scale treatment wetlands using coco coir, biochar, and sand/gravel media exhibited higher removal efficiencies for most emerging contaminants compared with systems using gravel alone, in some cases, adsorbing nearly 100% of contaminants in synthetic wastewater at high concentrations. These results were observed across different flow configurations and hydraulic retention times, and were attributed to the high BET surface area, porosity, and grain size variability of these materials.

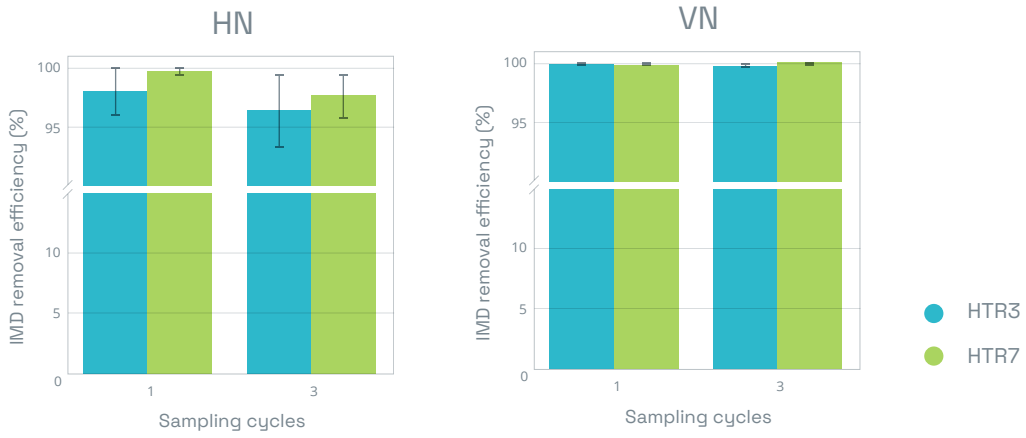


Figure 3.2

Removal efficiency of imidacloprid (IMD) in vertical and horizontal lab-scale treatment

The findings also highlight additional advantages of using waste-derived substrates with adsorption capacity. Laboratory-scale adsorption experiments and NbS trials provide a practical and reliable approach to identifying suitable materials. However, for successful implementation, substrate selection must consider more than adsorption performance alone. Key factors include hydraulic behaviour, potential secondary contamination, long-term sustainability, and operational feasibility.

Comprehensive material characterization is strongly recommended to guide selection and should include:

- **Granulometry and particle size distribution**
- **BET surface area and porosity**
- **Leachate analysis to detect potential secondary contaminant release**
- **Adsorption tests for relevant target contaminants**

Additional considerations for practical deployment include:

- Type, concentration, and composition of the contaminants and wastewater
- Hydraulic retention time and system design
- Material availability, cost, and associated risks
- Use of larger particles to reduce clogging and facilitate maintenance
- The need for lifespan studies to determine replacement schedules and optimize costs and efficiency
- Potential integration of post-treatment filters using these materials to prevent clogging, especially in treatment wetlands for domestic wastewater, and to facilitate replacement when needed

By systematically evaluating these factors, NbS designers can select substrates that not only maximize contaminant removal efficiency but also ensure long-term operational reliability, sustainability, and adaptability under varying conditions. Table 3.2: presented summary of substrates utilized in Nature-based Solutions for water treatment is presented based on review most update publications. The analysis of substrates used in Nature-based Solutions (NbS) for water treatment demonstrates that material selection strongly influences pollutant removal efficiency. Among the studied media, activated carbon, biochar, expanded clay, and zeolite exhibit the most versatile and high-performance treatment capacities. Activated carbon shows excellent adsorption of organic pollutants, including pesticides and endocrine-disrupting compounds, and achieves high chemical oxygen demand (COD) and total nitrogen (TN) removal. Biochar presents strong sorption potential for both inorganic and organic contaminants, particularly heavy metals and pharmaceuticals, while also supporting denitrification processes. For nutrient removal, alum sludge, slag, expanded clay, and zeolite demonstrate notable effectiveness. Alum sludge and slag are especially efficient for phosphorus adsorption, whereas zeolite exhibits superior ammonium removal due to its ion-exchange properties. Expanded clay provides balanced performance, supporting phosphorus and ammonium removal while enhancing biofilm development.In terms of heavy metal removal, biochar, expanded clay, fly ash, limestone, and zeolite show strong adsorption capacity. Regarding emerging contaminants, activated carbon and biochar remain the most effective materials, followed by expanded clay and zeolite, which demonstrate removal potential for antibiotics, pesticides, and other micropollutants.

Conversely, commonly used natural materials such as gravel, sand, lava rock, perlite, and pumice are primarily valued for their hydraulic properties and low cost, but generally exhibit lower or more variable pollutant removal efficiencies unless combined with more reactive substrates. Overall, reactive and high-porosity materials with strong adsorption or ion-exchange capacities provide the most comprehensive treatment performance in treatment wetlands and other nature-based systems.

Table 3.2

Summary of substrates utilized in Nature-based Solutions for water treatment

Material adsorber/ Based medium	NbS	Source	Material composition	Treated water
Activated carbon	Treatment wetland	Industrial	Active carbon or activated charcoal, plant (lignocellulosic)-based or coal (lignite, bituminous)-based	Synthetic wastewater
Alum sludge	Treatment wetland	Industrial	A waste product from the treatment of drinking water when aluminium salts are employed as the coagulants	Synthetic and real wastewater
Biochar	Treatment wetlands	Industrial	Produced by means of pyrolysis of agricultural biomass waste like straw, corn, wood, and dairy manure	Wastewater, mine drainage
Calcite	Treatment wetland	Natural	A carbonate mineral	Wastewater, agricultural runoff
Ceramsite	Treatment wetland	Industrial	It is produced by the ceramic production of raw materials by high-temperature calcination	Wastewater, greywater
Coconut subproducts	Treatment wetlands, Green walls	Natural	Fibre from coconut husk	Wastewater, synthetic greywater, landfill leachate

1 J. Liu et al. (2021) Water. 13. 476
2 Ruibin et al. (2019). Journal of Environmental Engineering Technology. 9. 145-150.
3 Daoguo et al. (2019). Journal of Environmental Engineering Technology. 9 552-558.
4 Zhao et al. (2015). Water Science Technology. 71. 1775-1782.
5 Zhao et al. (2011). Process Biochemistry. 46. 278-283.
6 Chand et al. (2022). Chemosphere. 307. 135975.
7 Feng et al. (2022). Chemical Engineering Journal. 444. 136636.
8 Garcia et al. (2013). Critical Reviews in Environmental Science and Technology. 40. 561-661.
9 Saeed et al. (2021). Environmental and Sustainability Indicators. 12. 100146.
10 Fan et al. (2022). Chemosphere. 301. 134762.
11 Danley-Thompson et al. (2015). Journal of Environmental Engineering. 142.
12 Abd-Ur-Rehman et al. (2023). hal04186669.

Advantages	Disadvantages	Emerging Contaminants adsorption	References
Good removal of chemical oxygen demand and total nitrogen; high adsorption capacity for organic pollutants	High cost; greater growth and reproduction of microorganisms; clogging potential	Good adsorption of pesticides and phenolic endocrine-disrupting compounds	60
Low cost; abundant; waste reuse; high efficiency for phosphorus removal	High transportation cost; nitrogen adsorption is not unanimous; clogging potential	Not found	20, 41, 47 [1] [2] [3] [4] [5]
Waste reuse; sorption capacity for various inorganic and organic contaminants; decrease greenhouse gas emissions; improve plant development; high porosity	Potential to release toxic substances; limited productivity; high costs of the production process; efficiency depends on the raw material	Good performance for pharmaceuticals and heavy metals removal	23, 73, 75, 146 [6] [7]
Good adsorption capacity of ammonium nitrogen and phosphorus	Nitrogen and phosphorus adsorption is not unanimous; clogging potential	Not found	20, 44, 259 [8]
Good removal of total phosphorus and total nitrogen; improves biofilm development; high porosity	Ammonium nitrogen removal is not unanimous	Good adsorption combined with other substrates (personal care products)	20, 54, 56 [9] [10] [11] [12]
Low cost; lightweight; waste reuse; high water retention; abundant	Wide variation in total nitrogen and ammonium removal; total phosphorus removal is not unanimous; clogging potential	Good performance for heavy metals, hydrophilic, hydrophobic, and xenobiotic organic compounds removal	84

Material adsorber/ Based medium	NbS	Source	Material composition	Treated water
Compost	Treatment wetlands, Green walls	Artificial	Nutrient-rich material produced through the decomposition of organic matter	Synthetic greywater, mine drainage
Expanded clay (Filtralite, LECA, etc.)	Treatment wetland, Green walls	Natural	Expanded clay	Synthetic and real wastewater, greywaters
Fly ash	Treatment wetland	Industrial	Solid waste discharged from coal-fired boilers, such as coal-fired power plants	Wastewater
Fyto-foam	Green walls	Industrial	Urea formaldehyde resin foam	Synthetic greywater
Gravel	Treatment wetland, Green walls and Green roofs	Natural	Rock fragments with SiO^2 and Al2O3 as main chemical components	Synthetic and real wastewater, greywaters
Lava rock	Treatment wetland, Green walls	Natural	Rock formed from lava erupted from a volcano	Wastewater, greywater

1 Gandy et al. (2016). Ecological Engineering. 97. 179-185.
2 N. Dal Ferro et al. (2021). Science of total Environment. 757. 144189.
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5 Barya et al. (2022). Ecohydrology. 15. e2424.
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10 Dias et al. (2020). International Journal of Environmental Research and Public Health. 17(22): 8592.

Advantages	Disadvantages	Emerging Contaminants adsorption	References
Low investment; simple technology; recycling of resources; high removal performance	Different composition; clogging potential	Good heavy metals removal	84 [1]
Improves biofilm and plant development; good hydraulic conductivity; good phosphorus removal; good chemical oxygen demand and ammonium removal	Different compositions and commercial types; clogging potential	Good pesticide and antibiotics removal; higher removal of lipophilic compounds; good heavy metals removal	50, 51, 52, 86 [2] [3] [4]
High porosity; waste reuse; good removal of chemical oxygen demand, phosphorus and total nitrogen	Different composition	Good heavy metals removal	64, 65, 66 [5]
Lightweight	Low to moderate water quality treatment performance; clogging potential; not ecological	Not found	27
Widely available and used; low cost; high permeability; low phosphorus removal	Chemical oxygen demand and total nitrogen removal capacity are not unanimous; lower pharmaceuticals removal capacity; different composition	Higher adsorption of sulfamethazine	24 [6] [7] [8]
High permeability	Low removal of chemical oxygen demand and total nitrogen	Lower emerging contaminants and heavy metals removal performance	83 [9] [10]

Material adsorber/ Based medium	NbS	Source	Material composition	Treated water
Limestone	Treatment wetland	Natural	Calcium carbonate	Wastewater
Oyster shell	Treatment wetland	Natural	A by-product of mariculture	Synthetic and real wastewater
Peat	Treatment wetland	Natural	A complex material with lignin, cellulose, and humic acids	Synthetic and real wastewater
Perlite	Treatment wetland, Green walls	Natural	Amorphous volcanic glass	Wastewater, greywater
Pumice	Treatment wetland, Green walls	Natural	Volcanic rock with silica as the main component	Wastewater, greywater
Sand	Treatment wetlands, Green walls	Natural	A set of small fragments of rocks, minerals, and marine animals' exoskeletons	Wastewater, synthetic greywater
Rockwool	Green walls	Industrial	Mineral rockwool fibre	Synthetic greywater

1 Nguyen et al. (2022). Water 14(20), 3325
2 Aregu et al. (2021). Environmental Systems Research. 10. 33.
3 Rozari et al. (2021). Heliyon. 7. e07423.
4 Sami et al. (2023). Journal of Environmental Management. 340. 117998.

Advantages	Disadvantages	Emerging Contaminants adsorption	References
Low cost and good usability	Low to moderate chemical oxygen demand and ammonium removal capacity; total phosphorus removal is not unanimous	Good adsorption of arsenic and heavy metals	33, 69, 70
Good filtration properties; lightweight; waste reuse; good phosphorus adsorption	Lack of performance information for the removal of other parameters	Lower adsorption of antibiotics; capacity to adsorb heavy metals	36, 37, 38 [1]
Improves denitrification; lightweight; good chemical oxygen demand removal	Phosphorus removal capacity is not unanimous; different compositions	Removal of glyphosate	41, 42
Lightweight; improves plant and fungi development; high water retention	Low to high performance for COD, BOD, TSS, TN, and turbidity removal	Improved emerging contaminants removal by plant uptake	46, 56, 86, 95
Lightweight; good hydraulic conductivity; improves plant development; good treatment performance compared to gravel	Better performance combined with other materials	Not found	86 [2 3 4]
Widely available and used; low cost; low phosphorus removal	Better performance combined with other materials; mostly used with gravel; different composition	Not found	19, 20, 28, 29
Lightweight; high water retention	Low to moderate water quality treatment performance; clogging potential; not ecological	Not found	27

Material adsorber/ Based medium	NbS	Source	Material composition	Treated water
Rice straw	Treatment wetland	Natural	Agricultural waste composed of cellulose and lignin	Water from a eutrophic river
Sawdust	Treatment wetland, Green walls	Natural	Substrate produced from natural wood, composed mainly of cellulose, polyoses, and lignin	Wastewater, rainfall
Slag	Treatment wetland	Industrial	Blast furnace slag and steel slag	Wastewater
Vermiculite	Treatment wetlands, Green walls	Natural	Hydrated magnesium aluminium silicate	Greywater
Zeolite	Treatment wetland	Natural, Industrial	Microporous aluminosilicate minerals	Synthetic and real wastewater, acid waters, rainwaters

1 Fahim et al. (2019). Environmental Science and Pollution Research. 26, pages20400–20410
2 Barca et al. (2013). Environ. Sci. Technol. 2013, 47, 1, 549–556
3 Thomaidi et al. (2022). Science of the Total Environment. 807. 151004.
4 Stefanatou et al. (2024). Science of the Total Environment. 906. 167362.
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6 V. Prodanovic et al. (2017) Ecological Engineering. 102. 625-635.

Advantages	Disadvantages	Emerging Contaminants adsorption	References
Low cost; waste reuse; improves denitrification; improves plant development; good removal performance	Lack of studies on capacity	Not found	53
Lightweight; improves denitrification; moderate TSS, nitrate and phosphorus removal	Clogging potential; different composition	Not found	97 [1]
Good adsorption capacity of phosphorus and ammonium	Release of CaO slag under some conditions	Not found	55, 61, 62, 63 [2]
Lightweight; good removal of organic pollutants	Clogging potential; low to high water quality treatment performance	Not found	95 [3 4 5 6]
High porosity; good ammonium and chemical oxygen demand removal	Low to moderate phosphorus removal capacity	Removal capacity for heavy metals and antibiotics	30, 31, 32, 33, 34, 35, 157

This deliverable presents a comprehensive set of technical and operational guidelines that support the design, implementation, integration, and management of innovative Nature-based Solutions (NbS) developed and validated within the NICE project. The document translates the experience gained in the Urban Real Labs into structured, practice-oriented guidance aimed at facilitating the replication and upscaling of these solutions in diverse urban contexts.

By compiling recommendations for **rain gardens**, **green walls**, **multi-stage treatment wetlands**, and **vertical-flow treatment wetlands for CSO treatment**, the deliverable contributes to bridging the gap between research demonstration and real-world deployment. Particular attention has been given to emerging and less-standardised solutions, for which consolidated technical guidance was previously limited, ensuring that the knowledge generated in NICE can effectively support future implementations.

The alignment of the presented solutions with the **IUCN Global Standard for Nature-based Solutions** further strengthens their relevance, demonstrating their capacity to address societal challenges while ensuring environmental integrity, economic feasibility, and adaptive governance. This alignment supports the positioning of NICE solutions within broader European strategies related to climate resilience, urban water management, and sustainable infrastructure.

Overall, the guidelines are intended to serve as a practical reference for municipalities, planners, engineers, water utilities, and decision-makers seeking to implement NbS-based water management solutions. The knowledge compiled in this deliverable contributes to the long-term sustainability and mainstreaming of Nature-based Solutions, supporting their wider adoption beyond the NICE project.

Annex

ABBREVIATIONS TABLE

TW	Treatment Wetland
CEC	Contaminants of Emerging Concern
WW	Wastewater
HTR	Hydraulic Retention Time
VF	Vertical Subsurface Flow Treatment Wetland
HF	Horizontal Subsurface Flow Treatment Wetland
VI	Inoculated Vertical Subsurface Flow TW
HI	Inoculated Horizontal Subsurface Flow TW
VN	Non - Inoculated Vertical Subsurface Flow TW
HN	Non - Inoculated Horizontal Subsurface Flow TW
NH_{4+}	Ammonium
COD	Chemical Oxygen Demand
BOD	Biological Oxygen Demand
KN	Kiejdahl Nitrogen
EC	Electrical conductivity
ORP	Redox potential
NO_3-	Nitrate
NO_2-	Nitrite
TN	Total nitrogen
TP	Total phosphorus
TSS	Total Suspended Solids

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