MULTISOURCE

The Economics of Nature-based Solutions for Wastewater Treatment

Deliverable 3.2

This project has received funding from the European Union’s Horizon H2020 innovation action programme under grant agreement 101003527.

D3.2 – Cost-benefit functions and results	D3.2 – Cost-benefit functions and results
Work Package	WP3 Business Models
Dissemination Level	Public
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Date Due	30 November, 2023
Date Submitted	30 November, 2023
File Name	MULTISOURCE D3.2 REVISED RP2
Status	submitted
Reviewed by (if applicable)	Jaime Nivala, Maria Wirth
Suggested citation	Panduro, Abate & Jensen (2023) The Economics of Nature-based Solutions for Wastewater Treatment. MULTISOURCE Deliverable D3.2 – Cost-benefit functions and results, H2020 grant no. 101003527

This document has been prepared in the framework of the European project MULTISOURCE. This project has received funding from the European Union's Horizon 2020 innovation action programme under grant agreement no. 101003527.

Summary

This report introduces a robust and comprehensive cost-benefit analysis (CBA) methodology for evaluating nature-based solutions for wastewater treatment (NBSwt). Developed under the Horizon project MULTISOURCE funded by the European Union, the CBA framework is designed to be highly adaptable, catering to diverse contexts including both developed and developing countries. The methodology employs a modular structure, incorporating generic cost and benefit functions that allow users to tailor the analysis to local conditions and water management objectives.

The CBA accounts for a wide array of economic factors, from direct costs and returns to externalities such as pollution contaminants. It is grounded in state-of-the-art cost and benefit transfer models and draws from an extensive body of scientific literature. The framework will be integrated with the MULTISOURCE Technology Selection Tool and the Planning Platform to ensure user-friendly application and consistency.

The report also discusses the economic implications of various NBSwt systems, emphasizing the role of land opportunity costs and the importance of context-specific assessments. It acknowledges the limitations inherent in existing cost and benefit estimates and suggests avenues for more precise, region-specific evaluations.

Keywords: cost-benefit, economics, land-use opportunity cost, wastewater treatment, nature-based solutions

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1.0 Introduction

Water treatment is a crucial aspect of sustainable development, as it ensures the availability of clean and safe water for human consumption, agriculture, industry, and the preservation of natural ecosystems (UN-Water, 2018). In a world facing increasing water scarcity, pollution, and climate change impacts, effective water treatment is essential for maintaining public health, economic productivity, and environmental resilience (World Health Organization [WHO], 2017; World Bank, 2019). The growing global population and urbanization trends further amplify the need for efficient water treatment solutions, as these factors place significant pressure on water resources and infrastructure (United Nations, 2018). Moreover, untreated wastewater and the release of pollutants into water bodies can have severe consequences for aquatic ecosystems, leading to biodiversity loss, eutrophication, the disruption of ecological processes, and human health impacts (Vörösmarty et al., 2010; WWAP, 2017). By addressing these challenges, water treatment plays a pivotal role in achieving several United Nations Sustainable Development Goals (SDGs), including clean water and sanitation (SDG 6), good health and well-being (SDG 3), and life below water (SDG 14) (United Nations, 2015). Consequently, developing innovative, cost-effective, and environmentally friendly water treatment methods, such as nature-based solutions, is of paramount importance for ensuring the long-term sustainability of our planet's most precious resource: water (Cohen-Shacham et al., 2016).

Nature-based solutions (NBS) are innovative approaches that harness the power of ecosystems to address various societal challenges, such as water management, climate change adaptation, and biodiversity conservation (Cohen-Shacham et al., 2016). In the context of water treatment, capitalize on the inherent capabilities of ecosystems, such as wetlands, forests, and riparian vegetation, to filter, absorb, and break down pollutants, thereby improving water quality and reducing the need for conventional treatment methods (UN-Water, 2018). The implementation of NBS for water treatment presents a significant opportunity for cost savings, as these solutions often require lower capital investments and operational costs compared to traditional water treatment infrastructure (Brauman et al., 2017). Moreover, nature-based solutions offer multiple co-benefits, including carbon sequestration, habitat creation, flood mitigation, and recreational opportunities, which can enhance the overall well-being of communities and contribute to more sustainable and resilient landscapes (Mayerhofer et al, 2015; Seddon et al., 2020).

While NBSs have gained recognition for their potential benefits, it is important to acknowledge the potential issues they may entail. Scalability poses a challenge as implementing NBS on a large scale may prove difficult. Additionally, performance variability could hinder their effectiveness, as outcomes may vary depending on specific environmental conditions. The long-term viability and maintenance of NBS must also be considered to ensure their sustained benefits. Moreover, land and space requirements could restrict their implementation in densely populated areas. Another limitation is the limited treatment capacity of NBS, which may pose constraints on their applicability to large-scale environmental challenges.

In this report, we endeavor to explore the economic viability of nature-based solutions for water treatment (NBSwt) in comparison to traditional water treatment methods and to identify the specific situations and scenarios in which NBSwt can compete for cost-effectiveness with conventional approaches. By providing a robust economic assessment framework, we aim to support decision-makers in making informed and efficient choices regarding water treatment strategies. Through a comprehensive cost-benefit analysis, our methodology considers the various direct and indirect benefits of NBSwt, as well as the context-specific factors that can influence their competitiveness. By examining diverse situations and scenarios, this report will not only shed light on the potential of NBSwt as a viable solution for different water treatment needs but also guide stakeholders in determining when and where these innovative and sustainable approaches can be most effectively implemented.

2.0 What are nature-based solutions for water treatment

2.1 Nature-based solutions in general

NBS are innovative approaches that utilize the natural processes and functions of ecosystems to address a wide range of societal challenges, such as climate change adaptation, water management, biodiversity conservation, and disaster risk reduction (Cohen-Shacham et al., 2016; Bauduceau et al, 2015). By working with and enhancing nature, NBS promote the sustainable use of natural resources while providing multiple environmental, social, and economic benefits. These solutions harness the inherent capabilities of ecosystems, such as wetlands, forests, and riparian vegetation, to deliver valuable services such as water purification, flood protection, carbon sequestration, and habitat creation (Seddon et al., 2020). As a sustainable and holistic approach, NBS provide a vital alternative to conventional, infrastructure-heavy methods, offering a more resilient and adaptable means of addressing pressing global issues while supporting the overall health and well-being of both human and natural systems.

2.2 Wastewater treatment

NBS can effectively provide secondary wastewater treatment services by utilizing the inherent capabilities of ecosystems to filter and break down pollutants from wastewater. One example of NBS for water treatment is the use of constructed wetlands, which are engineered systems designed to mimic the natural processes occurring in wetland ecosystems. These wetlands typically consist of shallow basins filled with aquatic plants and permeable substrates, such as gravel, sand, or soil, which support the growth of microbial communities. As wastewater flows through the wetland, the plants, substrates, and microbes work together to remove suspended solids, organic matter, and nutrients, such as nitrogen and phosphorus, from the water (Kadlec & Wallace, 2008).

Another example of NBS for secondary water treatment is the use of vegetated filter strips or buffer zones, which are planted areas adjacent to water bodies, such as rivers or lakes. These strips serve as a barrier, capturing and treating surface runoff from agricultural or urban areas by slowing down the flow of water, promoting infiltration, and allowing pollutants to be filtered and absorbed by plants and soil (Borin et al., 2010).

The treated water from nature-based secondary treatment systems can be used for various non-potable purposes, such as irrigation, landscaping, and groundwater recharge, thereby contributing to the sustainable management of water resources and reducing the demand for freshwater (UN-Water, 2018). See the appendix for a more technical description of NBSwt.

2.3 Multiple benefits of nature-based solutions for water treatment

NBS are recognized for their multipurpose characteristics, offering a range of environmental, social, and economic benefits that can be tailored to address the specific challenges and needs of different urban areas. The services provided by NBS are highly context-dependent, as the characteristics of the natural environment and the prevailing local challenges, such as air pollution, noise, water management, or biodiversity loss, can greatly influence the design and functionality of these solutions (Cohen-Shacham et al., 2016). By harnessing the power of ecosystems and working in harmony with nature, NBS can be customized to address multiple issues simultaneously while creating resilient, healthy, and sustainable urban landscapes.

The following list outlines some of the general services that can be provided by NBS and are not specific to NBS for water treatment:

- Air pollution: NBS, such as green roofs, urban forests, and vegetated walls, can help mitigate air pollution by capturing and absorbing airborne pollutants, thus improving air quality in urban areas (Nowak et al., 2006).
- Noise mitigation: Vegetated barriers, such as hedges or trees, can effectively reduce noise levels by absorbing and scattering sound waves, creating quieter and more pleasant urban environments (Van Renterghem & Botteldooren, 2009).
- Water flow and flood prevention: NBS, such as permeable pavements, rain gardens, and constructed wetlands, can promote water infiltration, reduce surface runoff, and mitigate the risk of urban flooding (Fletcher et al., 2013).
- Carbon sequestration: Ecosystems like urban forests and green spaces can act as carbon sinks, absorbing and storing atmospheric carbon dioxide, thus contributing to climate change mitigation efforts (Nowak & Crane, 2002).
- Biodiversity: NBS can enhance urban biodiversity by creating diverse habitats and ecological corridors for flora and fauna, thereby supporting the resilience and functioning of ecosystems (Kowarik, 2011).
- Recreational services: NBS, such as parks, urban gardens, greenways, and waterfront promenades, can offer a wide range of recreational opportunities for urban residents, including walking, cycling, picnicking, and birdwatching (Panduro & Veie, 2013).
- Well-being and health: NBS can also enhance mental well-being by providing peaceful and aesthetically pleasing environments for relaxation and stress relief (Hartig et al., 2014; Maas et al., 2009).

See the chapter ‘Benefits of NBSwt’ for specific services provided by NBSwt.

3.0 MULTISOURCE project pilots

Six pilots are associated with the MULTISOURCE project. The pilots showcase the diverse range of nature-based solutions for water treatment (NBSwt). These pilots, implemented in various geographical and socio-economic contexts, demonstrate the adaptability and versatility of NBSwt in addressing water treatment challenges while also highlighting their potential to deliver multiple environmental, social, and economic benefits tailored to the specific needs of each locality. In the following, each of the pilots is described.

3.1 t' Hof Bellewaerde, Ypres, Belgium: Phytoparking System

A phytoparking system has been implemented at the t' Hof Bellewaerde camping site in Ypres, Belgium – se the facility in figure 1. Traditional methods of wastewater treatment and drinking water installations are prohibited in the area due to historical reasons that prevent excavation. This natural wastewater treatment solution uses expanded clay aggregates placed beneath a parking space - in this case, a bicycle shed. The system includes two separate basins for treating black water and grey water. Approximately 30% of the treated grey water can be reused for toilet flushing. During the summer months, additional filtration and disinfection processes enable the grey water to be repurposed as drinking water when the supply of drinking water, typically derived from purified rainwater, is limited (Watercircle 't Hof Bellewaerde, n.d.).

Figure 1 – Show the phytoparking system that partly treats water and partly works as a bicycle shed

(Watercircle 't Hof Bellewaerde, n.d.)

The phytoparking system spans 75 m² and is designed to accommodate 130 camping guests. The construction cost amounted to 65,000 EUR, and the annual maintenance expense is estimated at 350 EUR (M. Martens, personal communication, August 23, 2022).

3.2 Leipzig, Germany: Green Roof Pilot

In Leipzig, Germany, the pilot features five green roofs, each covering an area of 25 m² - see figure 2 that present an overview of the green roof facility. Constructed in 2019, the green roofs primarily serve to prevent flooding by retaining rainwater in a drainage layer situated beneath the vegetation. Additionally, these green roofs contribute positively to biodiversity and provide a cooling effect for the buildings they cover (MULTISOURCE, 2021).

The construction costs associated with this pilot project do not accurately reflect typical real-world expenses, as the green roofs in question were specifically constructed for scientific research purposes (J. Friesen, personal communication, August 23, 2022). For standard extensive green roofs, the median investment cost is approximately 108 EUR per square meter, with annual maintenance costs of 2.33 EUR per square meter. In contrast, intensive green roofs have a median investment cost of 269 EUR per square meter, and the corresponding annual maintenance costs are 7.5 EUR per square meter (Panduro et al., forthcoming).

Figure 2 – Show the green roof test center in Leipzig

(UFZ, n.d.)

3.3 Merone, Italy: Vertical Flow Aerated Wetland Pilot

The pilot in Merone, Italy, consists of a vertical flow (VF) aerated wetland designed to treat combined sewer overflow upstream of the centralized wastewater treatment plant in Merone (IRIDRA, n.d.). The wetland, constructed in 2020, aims to increase resilience to extreme events and reduce pressure on sewers (MULTISOURCE, 2021). Designed for a population equivalent of 13,000, the system occupies a surface area of 5,500 m² (MULTISOURCE, 2021). In figure 3 the outline of the naturebased solution is presented in conjunction with

The system is composed of various components: a pumping station with a maximum capacity of 1,430 m³/h; medium-fine screening (6 mm mesh) of rainwater using two screw filters, each with a maximum capacity of 200 l/s; sand removal via two parallel longitudinal aerated sand traps, each with a capacity of 200 l/s; and a pumping station for first flush rainwater. This pumping station is equipped with four 100 l/s pumps, separate delivery, and is connected to a constructed wetland basin (Qmax 400 l/s) to supply the aerated vertical submerged flow constructed wetland system. The aerated vertical submerged flow constructed wetland system is modified for combined sewer overflow, extending over 4,000 m² and divided into two 2,000 m² basins, each further divided into two 1,000 m² sectors. Additionally, there is a

1,500 m² free-flow constructed wetland system, designed to facilitate landscape integration and the creation of humid biotopes with high biodiversity.

Figure 3 – illustrates the vertical flow wetland area constructed in connection with a classical water treatment facility

(A. Rizzo, personal communication, September 2, 2022).

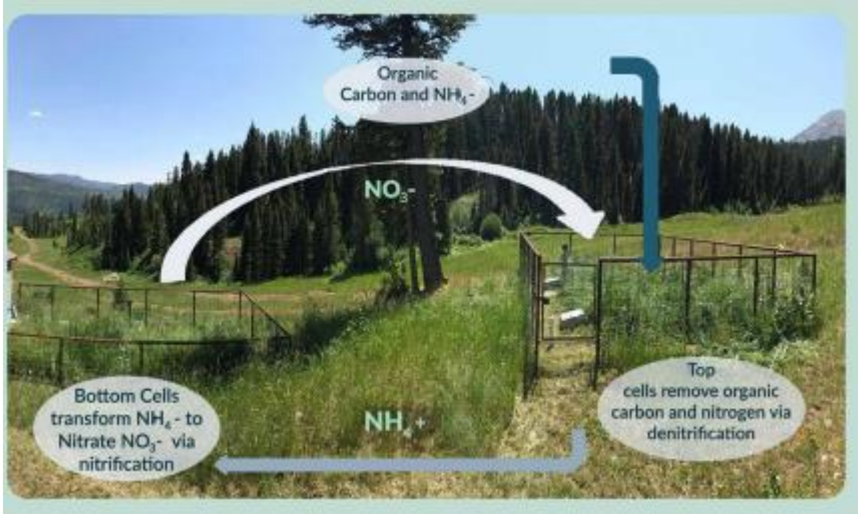
The total construction cost for the constructed VF wetland amounts to 1,512,931.12 EUR, which includes the execution of work, labour costs, and implementation of security measures. The annual maintenance cost is estimated at 22,500 EUR, covering the upkeep of plant essences, electricity, and green area management. The annual management cost is approximately 36,800.00 EUR, encompassing extraordinary maintenance and the disposal costs of grating and sand (A. Rizzo, personal communication, September 2, 2022).

3.4 Bridger and Bozeman, USA: Wetland Pilots

MULTISOURCE collaborates with two wetland pilot projects in the United States, one at Bridger Bowl Ski Resort in Bridger, and another in Bozeman.

In Bridger, a two-stage vertical flow (VF) wetland was constructed in 2013 to provide secondary treatment of wastewater from the resort. The wetland features a top cell, where recirculating sand filters were replaced with native plants for nitrogen removal via denitrification, and a bottom cell for nitrification (Bridger Bowl, n.d.). The wetland treats 7.5 m^3 of water per day, and both stages cover a total area of 95 m^2. As the wetland serves as a ski resort facility, it operates only during the winter season. The installation cost was 45,600 EUR, excluding labor for design and construction, which was donated. The yearly maintenance cost is estimated at 913 EUR (O. Stein, personal communication, September 22, 2022).

Figure 4 – Show the two-stage vertical flow (VF) wetland in Bridger along with the nitrogen processes in the facility



(O. Stein, personal communication, September 22, 2022)

The Bozeman wetland is also a two-stage vertical flow wetland, with construction planned for completion in November 2022. Designed to treat raw domestic water, this wetland will process 7.5 m³ per day, with both stages occupying a total area of 57 m². The labour cost for the construction was donated. The remaining installation cost amounts to 100,500 EUR (O. Stein, personal communication, September 22, 2022).

3.5 Girona, Spain: Modular Green Wall Pilot

The MULTISOURCE pilot in Girona, Spain, known as the Modular Green Wall (Mur Verd Modular), is under construction at the headquarters of the research institute ICRA (Institut Català de Recerca de l'Aigua) in Girona. This pilot serves as a hybrid system for greywater treatment, utilizing both vertical and horizontal flow treatment units to treat the greywater generated by the research institute. Designed to replicate natural processes occurring in constructed wetlands, the pilot initially consists of three treatment sectors, with plans to add three more. Each sector comprises a vertical and a horizontal flow module. The vertical flow modules feature five parallel vertical flow units, while the horizontal flow modules consist of three horizontal flow units, treating water sequentially (Institut Català de Recerca & de l'Aigua, 2022).

The completed wall, spanning all six sectors, will have a total surface area of 30 m² and stand 4 meters high. Each sector is estimated to have a treatment flow of 50 liters per day, resulting in a total treatment capacity of 300 liters daily for the entire Green Wall. The investment budget for the Green Wall is 45,691.13 EUR, covering expenses for wastewater pretreatment, construction, equipment, planters, pipes, sanitation, control and regulation, security and health, wastewater treatment, and irrigation water for the Green Wall itself. Adding 13% for general expenses and 6% for industrial profit, the total budget amounts to 54,372.45 EUR (Institut Català de Recerca & de l'Aigua, 2022). The investment budget for one sector is 17,952.64 EUR (Institut Català de Recerca, n.d.).

Figure 5 – Illustrate an example of a modular green wall

(Citygreen, n.d.)

3.6 Oslo, Norway: Raingarden and Stormwater System Pilot

The MULTISOURCE pilot in Oslo, Norway, consists of a raingarden that is part of a larger roadside stormwater system designed to store and treat runoff stormwater (S. Karlstrøm, personal communication, November 17, 2022). The pilot raingarden measures 30 meters in length and 1.7 meters in width (S. Karlstrøm, personal communication, November 17, 2022).

The entire project comprises five raingardens ranging from 10 to 30 meters in length, as well as an underground stormwater basin. Retention and treatment volumes have not been measured, nor have annual maintenance costs been calculated. However, the raingardens are designed to require minimal maintenance, with the primary tasks being to ensure that inlets beneath the pavement remain open and to conduct mowing approximately every three years. The construction cost for the whole project is 103,598 EUR. While there are no records of individual raingarden costs since the pilot raingarden was already established before joining MULTISOURCE, an educated guess for its construction cost would be around 38,409 EUR. Since becoming a MULTISOURCE pilot, an additional 655 EUR has been spent on test equipment, measuring cabinets, and a few extra small basins (S. Karlstrøm, personal communication, November 17, 2022).

Figure 6 – Show a part of the raingarden project in Oslo

(S. Karlstrøm, personal communication, November 17, 2022).

4.0 Cost-benefit analysis framework

Cost-benefit analysis (CBA) is a widely used evaluation method in economics that aims to assess the feasibility of a project or policy by comparing its costs and benefits (Boardman et al., 2017). The primary purpose of CBA is to determine whether the benefits of a project outweigh its costs, thereby facilitating informed decision-making. This analytical approach is particularly useful for assessing NBSwt, as it enables decision-makers to assess the economic feasibility of NBSwts and compare them to traditional water treatment methods in terms of their overall economic efficiency (Cohen-Shacham et al., 2016).

A crucial aspect of CBA is the establishment of baselines, which serve as reference points for determining the costs and benefits associated with different scenarios (HM Treasury, 2018). These scenarios represent various possible outcomes or actions, enabling stakeholders to assess the consequences of choosing one option over another. It is essential to consider both market goods (e.g., water quality improvements) and non-market goods (e.g., biodiversity enhancement) when conducting CBA, as this ensures a comprehensive understanding of the full range of benefits and costs associated with each scenario (Hanley & Barbier, 2009).

In CBA, future costs and benefits are typically discounted to reflect their present value, taking into account the time value of money (Arrow et al., 1996). This process, known as discounting, enables stakeholders to compare the net present value (NPV) of different scenarios, considering that benefits and costs may occur at different points in time. A higher NPV indicates a more favorable outcome, making it an essential metric for decision-making (Weitzman, 2001).

4.1 Formal theoretical setup

The costs and benefits associated with NBSwt projects can be represented using mathematical notation and functional forms. These include construction costs (Cc), maintenance costs (Cm), the opportunity costs of land (Cl), internal benefits (Bi), and external benefits (Be). The internal benefit (Bi) pertains to the benefits derived from the immediate use of the treated water for applications such as household use, irrigation, and groundwater replenishment. Conversely, the external benefits (Be) encompass the prevented harm resulting from the elimination of contaminants, pollutants, and impurities during the wastewater treatment process, thereby rendering it suitable for safe disposal or reuse. These benefits include health benefits and environmental benefits. Each of these variables is denoted as a function of time (t) and can be influenced by various factors such as NBSwt characteristics, environmental conditions, and socio-economic variables.

To account for the time value of money, we employ the concept of present value (PV) and discount rate (r). The present value of each cost and benefit is calculated using the following formula:

$$PV(x) = \sum_{t=0}^{T} \frac{x(t)}{(1+r)^t} \tag{1}$$

where x represents the cost or benefit variable, and T is the time horizon of the analysis. The net value (NPV_{NBSwt}) of the NBSwt project can then be expressed as:

$$NPV_{NBSwt} = [PV(B_i)+PV(B_e)]-[PV(C_c)+PV(C_m)+PV(C_l)] \tag{2}$$

This theoretical framework allows for the exploration of various scenarios, such as different discount rates, time horizons, and environmental conditions, to understand the robustness of the NBSwt project's net benefit under various circumstances. Sensitivity analyses and comparative statics can be conducted to identify the key drivers of the NBSwt project's net benefit and assess how changes in these factors affect the overall results of the analysis.

Furthermore, this model can be extended to incorporate uncertainty and non-market benefits by incorporating stochastic variables, probability distributions, or qualitative assessments. This flexibility ensures that the model remains relevant and adaptable to a wide range of NBSwt projects and policy contexts.

4.2 Land opportunity cost

Land opportunity cost refers to the potential economic benefits that could be realized if a piece of land were used for an alternative purpose, rather than its current use (Tietenberg & Lewis, 2018). In other words, it represents the value of the next-best use of the land that is forgone when a specific land use decision is made (Balmford et al., 2002).

Land opportunity costs are an important factor in evaluating and comparing the economic feasibility of different land use options, particularly in the context of environmental and urban planning. By considering land opportunity costs, decision-makers can make more informed choices about the optimal allocation of scarce land resources to various uses, such as agriculture, industry, housing, or nature-based solutions like green infrastructure (Naidoo & Ricketts, 2006).

When assessing land opportunity costs, it is important to consider both the direct and indirect benefits associated with alternative land uses (Nelson et al., 2009). Direct benefits include the potential revenues generated from the sale or lease of the land, as well as any profits that could be made from utilizing the land for a specific purpose (e.g., housing, agriculture, tourism, or commercial development). Indirect benefits can include the positive externalities associated with alternative land use, such as improved air and water quality, increased biodiversity, carbon sequestration, and enhanced recreational opportunities (Turner et al., 2000).

To calculate the land opportunity cost, one should estimate the net present value associated with the alternative land use and compare this to the net present value associated with NBSwt (Heal, 2000). This can help identify the most economically efficient allocation of land resources and inform decisions about land use planning and management (Barbier, 2000).

The incorporation of land opportunity costs into the analysis of CBA offers a nuanced perspective in terms of determining the appropriate placement of NBSwt within different contexts, encompassing urban centers, small towns, and rural areas. This consideration is of paramount importance due to the considerable variability in land opportunity costs among these locations. Furthermore, this approach enables the evaluation of the potential utility derived from alternative land uses, including residential, industrial, or agricultural activities. By integrating the concept of land opportunity cost, decision-makers can gain a comprehensive understanding of the optimal utilization of land resources, thereby informing strategic decisions regarding the placement of NBS and the overall management of land.

The requirement for the approval of a NBSwt, such as a two-stage vertical flow wetland, is that the net present value (NPV) of the nature-based solution must be greater than the NPV of alternative land-use options. In other words, the decision-makers must ensure that the long-term economic, social, and environmental benefits associated with the nature-based solution outweigh the benefits of other potential land uses, such as housing development or agricultural expansion, when considering the time value of money. By establishing this criterion, decision-makers can justify the implementation of the nature-based solution as the most advantageous and sustainable choice for the community, providing the highest overall value in terms of environmental, social, and economic outcomes.

Formally Let NPV_{NBSwt} represent the net present value of the NBSwt, and NPV_{ALT} represent the net present value of alternative land-use options. The requirement for the approval of the NBSwt can be formally expressed as an inequality:

$$NPV_{NBSwt} > NPV_{ALT} \tag{3}$$

This inequality indicates that the net present value of the NBS must be greater than the net present value of alternative land-use options to justify its implementation.

4.3 How to calculate the net present value with alternative land use

Understanding the value of land is a crucial aspect of calculating the Net Present Value (NPV) for alternative land use options. When considering the economic value of a property, the formula below offers a simplified yet informative approach:

Value of property = (Construction cost + maintenance cost - depreciation) + Land value (4)

Construction Cost: This is the initial outlay required for erecting structures or implementing land-use projects. It's essential to consider not just the material costs but also labor and other overheads.

Maintenance Cost: This includes the ongoing expenses required for the upkeep of the property. Depending on the land use, this could range from minimal (e.g., natural landscapes) to significant (e.g., commercial complexes).

Depreciation: This represents the decline in the value of the physical structures over time. Various methods can be used to calculate this, such as the straight-line or the declining balance method.

Land Value: This is the intrinsic value of the land in its current state. It can be based on real sales data or sales listings for similar properties in the area. When calculating the NPV of alternative land uses, this value acts as a constant to which other variables are added or subtracted.

The construction, maintenance, and depreciation costs for NBS are treated in the next sections, we identify these costs by extracting cost information from actual cases implemented on market terms. The intrinsic land value can be more elusive. For this, real sales data or sales listings for similar properties provide valuable benchmarks. By subtracting the combined construction and maintenance costs and adding back any depreciation, one can arrive at an estimate of the intrinsic land value or alternatively look at the prices of empty lots for sale which price will reflect pure land opportunity cost.

This approach enables the comparison of different land use projects such as residential buildings, commercial developments, agricultural initiatives, or NBSwt on a common economic baseline. By isolating the land value, stakeholders can make more informed decisions about the most beneficial and sustainable land use options.

5.0 Calculating Land Opportunity Cost Using Listing Prices for Empty Lots

Listing prices for empty lots for sale in a particular area can serve as a direct measure of land opportunity cost. These prices reflect what the market is willing to pay for the land in its current state, without any structures or modifications. Therefore, they offer an invaluable baseline for evaluating the economic feasibility of different land use options, whether they be residential, commercial, agricultural, or nature-based solutions.

5.1 Data Collection and Methodology for Land Use Modelling

To construct a robust land use model, a comprehensive dataset was compiled that considers both the listing prices and contextual property information of empty lots and farmland across Denmark. On October 9, 2023, web scraping using the rvest package in R (Wickham, 2022) was employed to extract relevant data from two key sources:

boligsiden.dk: This platform aggregates listings of residential properties, including empty lots, available for sale through real estate agents in Denmark. It essentially covers almost the entire residential property market in the country.

landbrugssiden.dk: Similar to boligsiden.dk, but focused on farmland, this site offers a comprehensive overview of farmlands listed for sale by real estate agents in Denmark.

Post-data collection, the scraped information was geocoded using a fuzzy merge approach. This was done by cross-referencing the collected data with an existing dataset containing information on all addresses in Denmark from the DAWA register website (DAWA, 2023). The purpose of this step was to associate each listing with precise geographic coordinates, enabling more nuanced analyses. To add another layer of context to our model, an urban density measure was calculated for each postal code area. This measure describes the number of addresses per square kilometer and provides insights into the varying levels of urbanization across locations. The urban density data were then coupled with the previously scraped and geocoded listings.

The resulting dataset is comprehensive, including the listing price, size in square meters, and an urban density measure for each empty lot and piece of farmland. This dataset serves as the foundation for the land use model, allowing for a nuanced understanding of the economic implications of different land use options in various urban contexts.

5.2 Descriptive Statistics of Empty Lots Data

To build a nuanced land use model, empty lot data were segmented into three distinct categories through k-means clustering. These clusters signify varying degrees of urban density: rural areas, suburban areas, and urban areas. Table 1 provides descriptive statistics of the webscraped price and size for the three land-use areas along with the constructed urban density measure. More extensive descriptive statistics are provided in appendix B.

Table 1 - Descriptive statistics for land use models divided by rural, suburb and urban areas

Metric	**Rural Areas**	**Suburban Areas**	**Urban Areas**
Number of Observations	3,067	399	315
Mean Price (EUR)	94,902	245,418	593,949
Standard Deviation in Price (EUR)	99,647	301,206	316,888
Mean Size (m^2)	1,007	820.08	752
Mean Urban Density (addresses/km^2)	34.69	208.40	1,421

Urban areas have the highest mean listing price for empty lots, followed by suburban areas and then rural areas. This implies that the competition for space is highest in urban areas and lowest in the rural areas. The standard deviation in price is highest in urban areas, indicating a wide range of prices, possibly due to diverse land use potentials or zoning regulations. The rural areas have the largest mean lot size, followed by suburban and then urban areas. This could be indicative again that demand and competition for space differ between the three different land-use areas. As expected, urban areas have the highest mean urban density, followed by suburban and rural areas.

This dataset serves as the foundation for our economic land use model. The unique characteristics of these clusters offer valuable insights into how land value and opportunity costs can vary considerably depending on the degree of urbanization.

5.3 Land-use model results

Three separate Ordinary Least Squares (OLS) regression models were conducted under the assumption of linearity between the price of empty lots and the explanatory variables: size in m2 and address density per km2 - see table 2. Importantly, the intercept was not included in the estimator for any of the models. In the rural model with 3,067 observations, both explanatory variables were statistically significant, with an R2 value of 0.507. The suburban model, based on 399 observations, also showed statistical significance for both variables, having an R2 value of 0.497. The urban model, although based on a smaller sample size of 31 observations, had the highest R2 value of 0.904 but showed statistical insignificance for the address density per km^2.

It is worth noting that the R2 values should be interpreted cautiously since the models lack an intercept, altering the conventional interpretation of this statistic.

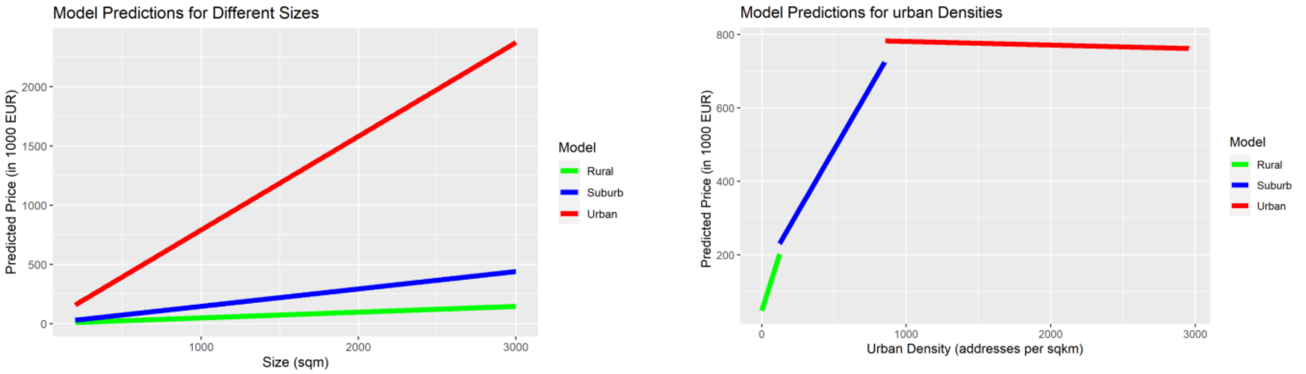
The absence of an intercept in the models could be particularly noteworthy given the high R2 values, suggesting that the models capture a substantial portion of the variance in prices even without accounting for a constant term. Residual standard errors and F statistics were reported for each model, all indicating a strong fit based on the significance levels.

Table 2 - Model estimates for land use models divided by rural, suburb, and urban areas

Regression Results			
	Rural	Surburb	Urban
Size (m^2)	48.468*** (2.429)	146.696*** (30.195)	790.865*** (92.276)
urban density (Address per km^2)	1,238.201*** (60.149)	679.477*** (116.237)	-9.805 (51.096)
Observations	3,067	399	31
R^2	0.507	0.497	0.904
Adjusted R^2	0.507	0.495	0.897
Residual Std. Error	96,600.980 (df = 3065)	276,024.500 (df = 397)	215,339.400 (df = 29)
F Statistic	1,578.773*** (df = 2; 3065)	196.177*** (df = 2; 397)	135.902*** (df = 2; 29)
Note:	$^{*}p<0.1$; $^{**}p<0.05$; $^{***}p<0.01$		

The parameter estimates for the size in *m*2 and address density per km^2 vary markedly across the three areas - rural, suburban, and urban. In rural areas, each additional square meter is estimated to increase the lot price by approximately 48.47 EUR, whereas in suburban and urban areas, the estimated increases are much higher at 146.70 EUR and 790.87 EUR, respectively. This suggests that land size has a more pronounced impact on prices in more densely populated areas. Similarly, for the variable of address density per km^2, the coefficient is positive and significant in both rural and suburban areas, estimated at 1,238.20 EUR and 679.48 EUR respectively. However, in urban areas, the coefficient is not statistically significant and is estimated to be -9.81 EUR. The difference in sign and magnitude across these areas indicates varying influences of urban density on empty lot prices. In the figures below the model interpretation for both size and urban density is presented.

Figure 7 - The relationship between price and size and price and urban density



5.4 Farm data

To complement the land use model, a dataset was constructed from landbrugssiden.dk, focusing on farmland properties across Denmark. Descriptive statistics are presented in Table three. The dataset contains 948 observations and covers a wide range of variables. The mean listing price is approximately 969,000 EUR, with a considerable range from 13 to 20.8 million EUR. Field sizes are typically measured in hectares, with an average size of 25 hectares and a range that spans from 1 to 670 ha. Residential building sizes follow a similar trend with a mean value of 222 m^2. The dataset is also rich in regional and farm-type indicators, such as the dummy variable for country estates that cover a majority of farmland for sale at 773 sales and cattle farms at 42, along with binary variables for geographic regions like Hovedstaden and North Zealand. This multifaceted dataset serves as the foundation of the land use economic model for farmland.

Table 3 - Descriptive statistics for the farmland land use model

Descriptive Statistics: continuous variables					
Statistic	N	Mean	St. Dev.	Min	Max
price (EUR)	942	970,723	1,521,434	39000	20,800,000
Size of field (ha)	942	25	50	1	670
Size of Building (m^2)	942	223	156	0	3,228
Age	942	1,791	467	0	2,021
Descriptive Statistics: dummy variables					
		zeros variable=0		ones variable=1	
Captial region	942	932		10	
Northern zealand region	942	887		55	
Zealand region	942	815		127	
Fyn region	942	852		90	
Southern Jylland region	942	793		179	
Western Jutland region	942	779		163	
Eastern Jutland region	942	776		166	
Northern Jutland	942	760		182	
Cattle farm	942	900		42	
Country estate	942	209		733	

Plant farm	942	829	113
Forest estate	942	921	21
Special estate	942	928	14
Pig farm	942	923	19

5.5 Farmland land-use model results

The OLS regression model for farmland is presented in table 4. The model has an R2 value of 0.871 explaining a larger degree of the variance in farm property prices. The model included 942 observations and considered variables such as field size, building size, age, farm types, and regional indicators. Of particular interest is the parameter estimate for the field size, which is 24,172 EUR/ha (with a standard error of 567). This estimate is statistically significant at the 0.01 level, making it a valuable metric for calculating land opportunity costs in farmland areas. Other variables like building size, age, and specific farm types also showed varying degrees of statistical significance. The F-statistic of 448.829 further confirms the model's strong explanatory power.

Table 4 - Model estimate for the farmland land use model

Regression Results: farmland model		
	Paramter β	Std. Error σ
Size of field (ha)	24,172***	(568)
Size of Building (m2)	2,095***	(145)
Age	-83*	(49)
Pig farm	-309,892*	(158,048)
Plant farm	-693,406***	(112,359)
Forest estate	-785,729***	(161,483)
Country estate	-489,708***	(114,314)
Special estate	-458,037**	(183,451)
Capital region	1,954,937***	(178,605)
Zealand region	34,243	(61,562)
Fyn region	-235,206***	(69,116)

Southern Jutland	-300,901***	(58,948)
Western jutland	-340,068***	(57,284)
Northern_jutland	-293,779***	(55,550)
Constant	711,727***	(145,661)
Observations	942	
R^2	0.871	
Adjusted R^2	0.869	
Residual Std. Error	549,792.500 (df = 927)	
F Statistic	448.829*** (df = 14; 927)	
Note:	*p**p***p<0.01	

5.6 Summing up the land opportunity cost

The concept of land opportunity cost plays a pivotal role in land use economics, serving as a basis for understanding the trade-offs associated with different types of land utilization. Our analysis has yielded robust model estimates that enable the calculation of land opportunity costs across various settings—farmland, rural, suburban, and urban areas.

Table 5 summarizes these calculations. For farmland, the opportunity cost is governed by the equation Price=24,172×Size in ha. For other land types, the opportunity cost can be described through a set of equations that account for both the size in m^2 and the address density per km^2. Importantly, these equations also have implications for NBSwt, which requires land and thus competes with other land uses. Measuring this opportunity cost is a critical element in the economic assessment of the viability of NBSwt. These equations serve as essential tools for policymakers, planners, and stakeholders, offering empirical insights into the economic implications of land use decisions.

Table 5 - Land opportunity cost retracted from land-use model estimates

type	Land opportunity cost
Farmland	Price= 24,172 ×Size in ha
Rural Areas	Price=48.468×Size in m^2+1,238.201×Address Density per km^2

Suburban Areas	Price=146.696×Size in m^2+679.477×Address Density per km^2
Urban Areas	Price=790.865×Size in m^2 - 9.8 x Address Density per km^2

6.0 Cost of construction

The construction cost of NBSwt, such as constructed wetlands, is influenced by several factors, including excavation, provision of filter materials, and planting of appropriate vegetation (Vymazal, 2011; Kivaisi, 2001). Excavation expenses depend on elements like soil type, topography, and wetland size, while the cost of filter materials is determined by their type and availability, such as gravel, sand, and clay (Kadlec & Wallace, 2009). The choice of vegetation also impacts cost. Native plant species are typically more affordable and better adapted to local conditions, however, they may not thrive in an NBSwt (Brix & Arias, 2005). Maintenance costs for these systems encompass the removal of larger organic and inorganic materials not captured during filtration, as well as routine inspection and maintenance of vegetation and other wetland components (Vymazal, 2011).

Cost estimates for the construction and maintenance of NBSwt have been extracted from both white and grey literature. White literature refers to published, peer-reviewed sources, while grey literature consists of unpublished or non-peer-reviewed materials such as reports and conference proceedings (Garousi et al., 2016). These cost estimates give an impression of the actual costs involved and can be utilized as part of a scoping exercise to assess the feasibility of a specific project (Kadlec & Wallace, 2009). It is important to note that costs can vary significantly based on factors such as labor costs, material expenses, and the availability of experienced industry professionals or companies specializing in constructing and maintaining nature-based wastewater treatment infrastructure (Vymazal, 2013). By examining specific examples or case studies, we can better understand how these cost factors play a role in the implementation of NBS. Ultimately, the cost estimates provided in the literature serve as a guideline for understanding the potential distribution of costs and the likely expenses associated with a particular nature-based wastewater treatment project (Morancho, 2003).

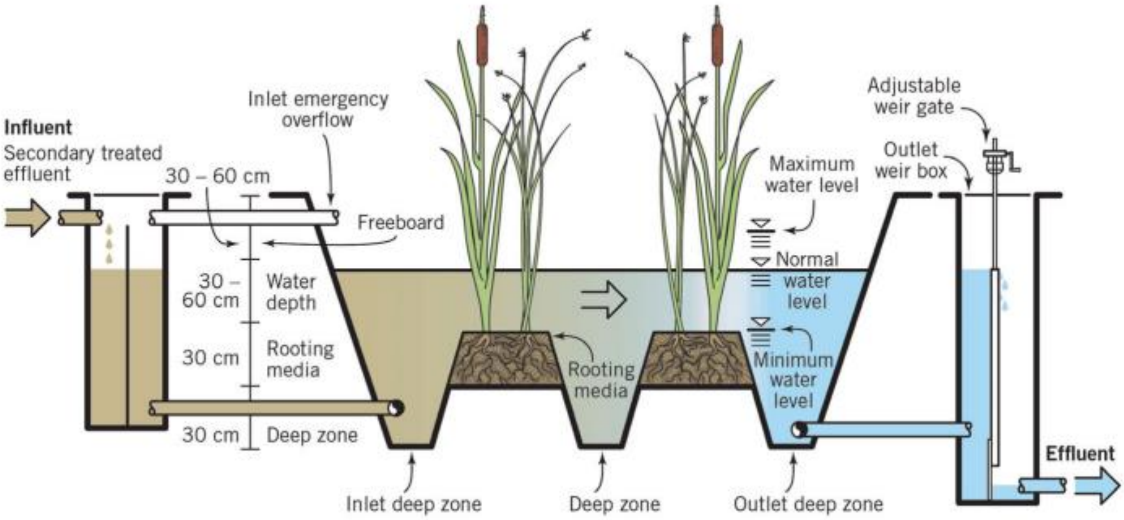
In the following subsection cost measures cost measure for the following NBSwt will be provided from both white and grey literature sources:

- Free water surface water treatment solution
- Horizontal sub-surface flow water treatment solution
- Vertical sub-surface flow water treatment solution
- Hybrid water treatment solutions

6.1 The cost of free water surface

In a free water surface (FWS) constructed wetland, wastewater flows freely through a flooded, vegetated area. As the water moves through the wetland, it undergoes physical, chemical, and biological treatment processes. This method is well-suited for wastewater that has already undergone secondary or tertiary treatment. Typically, the wetland is 10-45 cm deep and requires a larger surface area than subsurface treatment wetlands. As such, it is most appropriate for small urban communities where land is affordable and readily available. However, the open water surface containing wastewater presents some risks, including disease transmission and mosquito breeding (Eawag & Stauffer, n.d.-a).

Figure 8 - Free water surface constructed wetland area



* Figure Originally published in Dotro et al. (2021).

Table 6 presents the construction and maintenance costs linked to free water surface (FWS) treatment solutions. The costs are updated to reflect inflation and denominated in Euros as of fall 2022. Regarding the table, the median and mean treatment capacities are 5,524,000 and 12,714,000 m^3 per year respectively. When observing the construction costs, a notable disparity is seen between the median value of 363,166 EUR and the substantially higher mean of 828,750 EUR, which indicates that some cost observation pushes the mean cost high relative to the typical project. Operation and maintenance (O&M) costs, in contrast, show a relatively closer median and mean at 56,460 EUR and 50,743 EUR respectively.

Upon assessing the treatment costs per unit of flow, the median construction cost per m^3 per year stands at 0.526 EUR, while the average rises slightly to 0.621 EUR. The operation and maintenance costs per m^3 per year maintain a lower spectrum, with median and mean values at 0.027 EUR and 0.046 EUR respectively.

Additionally, the spatial demand of FWS constructed wetlands has been referenced from data by Vymazal & Kröpfelová (2008). The median space utilized is reported at 0.069 m^2/m^3/Year, with the mean somewhat higher at 0.117 m^2/m^3/Year. The data reveals a wide range, with the minimum value at a modest 0.005 m^2/m^3/Year and the maximum stretching up to 0.390 m^2/m^3/Year, indicating the variable space requirements depending on specific project parameters.

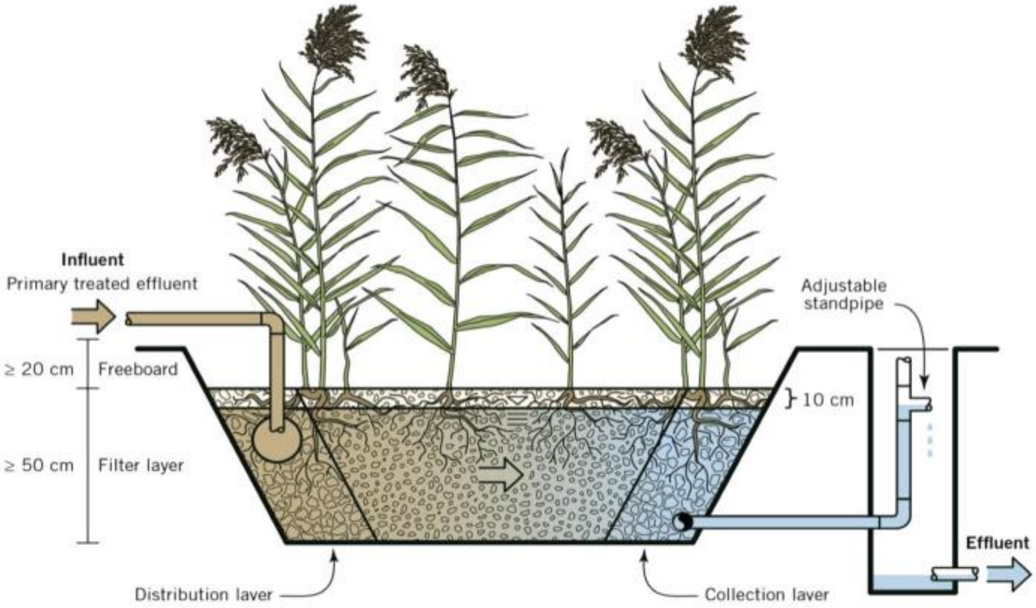
Table 6 - Cost of free water surface wetland area

Source	Country	year	Treatment (m^3/year)	Construction (EUR)	O & M (EUR)	Construction (EUR/ m^3/year)	O&M (EUR/ m^3/year)
US Army, 2003	United States	2001	138.1	205873	7918	1.4908	0.0573
US Army, 2003	United States	2001	138.1	344505	7918	2.4946	0.0573
Rousseau et al, 2004	Belgium	2003	318	205800		0.6472	
Tsihrintzis et al, 2007	Greece	2003	973	417683	1979	0.4293	0.0020
Hunter, 2019 (data)	United States	2017	1381	781040	56460	0.5656	0.0409
Hunter, 2019 (data)	United States	2017	1381	351544	56460	0.2546	0.0409
Hunter, 2019 (data)	United States	2017	5524	3634251	56460	0.6579	0.0102
Hunter, 2019 (data)	United States	2017	5524	1821282	56460	0.3297	0.0102
DiMuro et al, 2014	United States	1995	6900	2190667	178174	0.3175	0.0258
Hunter, 2019 (data)	United States	2017	6905	363166	56460	0.0526	0.0082
Hunter, 2019 (data)	United States	2017	12429	168872	56460	0.0136	0.0045
Hunter, 2019 (data)	United States	2017	20715	1296501	56460	0.0626	0.0027
Hunter, 2019 (data)	United States	2017	22096	365889	56460	0.0166	0.0026
Hunter, 2019 (data)	United States	2017	48335	274190	56460	0.0057	0.0012
Afzal et al., 2019	Pakistan	2014	57947	9991	6269	0.0002	0.0001

6.2 The cost of horizontal subsurface flow (HF/HSSF)

In a horizontal subsurface flow (HF/HSSF) constructed wetland, wastewater flows through an underground filter, typically made of gravel or sand, beneath the vegetated bed without any contact with the atmosphere until it reaches the outlet. The wetland is generally 60-80 cm deep and 25-30 m long. Horizontal flow wetlands are suitable for treating pre-treated wastewater. The water flow through the filter takes 2-5 days, depending on the climate, with the process being faster in warmer climates (Masi & Bresciani, n.d.-b).

Figure 9 - Horizontal Flow constructed wetland areas



* Figure Originally published in Dotro et al. (2021).

Table 7 provides an insightful overview of the treatment capacity and associated costs for horizontal flow constructed wetlands (HF). It reveals that the median annual treatment capacity for such systems is approximately 11,000 m^3. In terms of expenses, the median construction cost for an HF system is significantly higher at 13.945 EUR per m^3 per year, than the average construction cost of 8.133 EUR per m^3 per year. As for the operation and maintenance costs, the median value stands modestly at 0.134 EUR per m^3 per year. However, the mean operation and maintenance cost dramatically escalates to 1.255 EUR per m^3 per year. This stark difference suggests considerable variations in costs across different projects, highlighting the importance of specific site conditions, design considerations, and economic contexts in determining the overall expenditure.

Land cover values, according to Vymazal & Kröpfelová (2008), suggest that between 0.060 to 0.150 m^2 are required per m^3 per year. However, data from the same source indicates a median requirement of 0.063 square meters per m^3 per year, with an average of 0.97 square meters per m^3 per year. The minimum and maximum land cover requirements observed are 0.007 and 0.374 m^2 per m^3 per year, respectively (Vymazal & Kröpfelová, 2008).

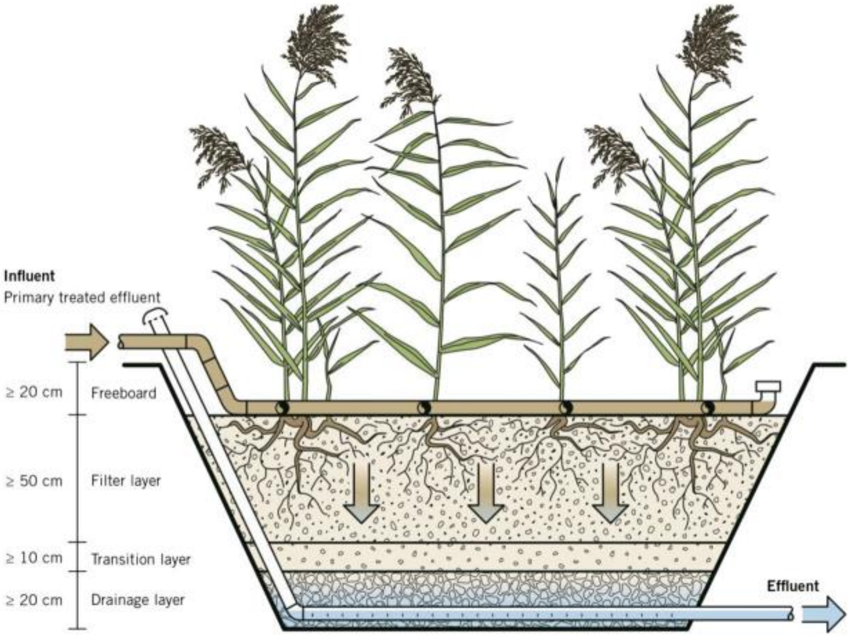
Table 7 - Cost estimates of Horizontal flow constructed wetland areas

Source	Country	Year	Treatment (Thousand m^3/year)	Construction (EUR)	O&M (EUR)	Construction (EUR/ m^3/year)	O&M (EUR/ m^3/year)
Mburu et al., 2014	Kenya	2011	1.1	659	112	0.59909	0.10182
Dallas et al., 2004	Costa Rica	2001	2.83	1320	16	0.46643	0.00565
Masi et al. (2006a)	Italy	2006	4.3	35920	720	8.35349	0.16744
Rousseau et al, 2004	Belgium	1999	8.1	379631		46.86802	
Temel et al. 2018)	Turkey	2018	8.6	123050		14.30814	
Nogueira et al. (2006)	Spain	2006	13.3	105250	12500	7.91353	0.93985
Rousseau et al, 2004	Belgium	2001	18.7	440462		23.55412	
Haberl et al. (1998)	Austria	1998	21.5	595500	178500	27.69767	8.30233
Riggio et al., 2018	Italy	2018	109.5	638812	283800	5.83390	2.59178
Puigagut et al. (2007)	Spain	2006	310.6	1198000	138000	3.85705	0.44430

6.3 Vertical subsurface flow (VF/VSSF)

In vertical subsurface flow (VF/VSSF) wetlands, pretreated wastewater flows through a filter of vegetation and gravel beneath the surface. In these wetlands, wastewater is poured vertically through inlets, passed down through the filter, and then collected by a drainage pipe before being discharged. The gravel filters out solids, while the vegetation supports a biological process that degrades nutrients and organic materials. Wastewater is poured through the filter in intervals (4 to 10 times a day) to intermittently starve the organisms. This approach prevents excessive biomass growth and increases porosity by drawing oxygen into the filter bed during the drainage process (Eawag et al., n.d.).

Figure 10 - Vertical Flow constructed wetland areas



* Figure Originally published in Dotro et al. (2021).

An examination of the cost measured presented in table 8 reveals considerable variations across different projects. On average, these systems have been designed to treat an annual flow of 66,000 m^3, with the median value noted at 43,500 m^3/year. In terms of expenses, the mean construction cost per flow, measured in m^3/year, amounts to 5.666 EUR, while the median is significantly lower at 3.666 Euros. The disparity between the two values indicates a wide range of costs between projects. Furthermore, the maintenance costs per flow also exhibit variability, with the mean and median values at 0.470 Euros and 0.130 Euros, respectively. This large range in both construction and maintenance costs can be attributed to site-specific conditions, differences in wetland design, and regional economic factors, all of which underline the complexity of implementing grey water treatment systems.

Table 8 - Cost estimates of Vertical flow constructed wetland areas

Source	Country	Year	Treatment (Thousand m^3/year)	Construction (EUR)	O&M (EUR)	Construction (EUR/ m^3/year)	O&M (EUR/ m^3/year)
Abdelhay, 2021	Jordan	2021	0.1	1725		17.250	
Shrestha et al., 2001	Nepal	1998	0.2	760		3.800	
Puigagut et al. 2007	Spain	2007	4.6	36609	3475	7.958	0.755
Shrestha et al., 2001	Napal	1997	7.3	23886		3.272	
Lienhoop, 2014	Jordan	2011	14	247637	29537	17.688	2.110
Rousseau et al, 2004	Belgium		21	16287		0.776	

TSIHRINTZIS et al, 2007:622	Greece	2003	66	509863	8637	7.725	0.131
Chen et al, 2008: 1989-1990	China	2004	73	40432	11895	0.554	0.163
US Army, 2003	United States	37104	138	487379	8006	3.532	0.058
US Army, 2003	United States	37104	138	627556	8006	4.548	0.058
Gajewska et al., 2016	Poland	2016	157	93000	2868	0.592	0.018
Yang et al., 2008	China	2001	175	52595		0.301	

6.4 Hybrid constructed wetland

A hybrid constructed wetland is a combination of vertical and horizontal flow wetlands, and sometimes other wetland types as well. By combining vertical and horizontal flow, treatment efficiency is increased, particularly in terms of nitrogen removal, where the two systems can complement each other. The presence of oxygen in vertical-flow wetlands allows for nitrification to occur, while horizontal flow wetlands enable partial denitrification. As a result, the treated water has significantly lower nitrogen levels. However, pre-treatment is still necessary (Stauffer & Spuhler, n.d.).

In table 9 cost measures for hybrid-constructed wetlands are presented. There are significant differences in the associated costs and treatment capacities. The average volume of grey water treated by these systems is 91,000 m^3 annually, whereas the median treatment capacity is notably less at 38,000 m^3/year. The construction cost per flow, gauged in m^3/year, exhibits variation with a mean value of 8.261 Euros and a median that is slightly higher at 9.764 Euros. As for the maintenance costs per flow, the mean and median are relatively closer at 0.347 Euros and 0.241 Euros, respectively. These variations across different projects can be attributed to the diversity of site conditions, design intricacies of the hybrid wetlands, and regional economic influences.

Table 9 Cost estimates of hybrid constructed wetland areas

Source	Country	Year	Treatment (Thousand m^3/year)	Construction (EUR)	O&M (EUR)	Construction (EUR/ m^3/year)	O&M (EUR/ m^3/year)
Resende, 2019	Brazil	2015	0.23	362	53	1.574	0.230

Resende, 2019	Brazil	2015	0.54	29	250	0.054	0.463
Puigagut et al. 2007	Spain	2006	5.5	27987	9922	5.089	1.804
Comas, 2004	Spain	2004	21	403175	7537	19.199	0.359
Gikas and Tsihrintzis, 2014	Greece	2006	23	309752	7705	13.467	0.335
Gkika et al, 2014	Greece	2010	29.565	345068	8749	0.012	0.000
Gkika et al, 2014	Greece	2010	30.66	330221	7801	10.770	0.254
Gkika et al, 2014	Greece	2010	32.85	333130	8286	10.141	0.252
Gkika et al, 2014	Greece	2010	43.8	527174	9309	12.036	0.213
Gkika et al, 2014	Greece	2010	49.275	462498	10274	0.009	0.000
Gkika et al, 2014	Greece	2010	54.75	597331	11532	10.910	0.211
Gkika et al, 2014	Greece	2010	65.7	688295	12403	10.476	0.189
Garfi et al. 2017	Spain	2017	106	336189	45500	3.172	0.429
Gkika et al, 2014	Greece	2010	164.25	1099541	23995	6.694	0.146
Gkika et al, 2014	Greece	2010	199.29	1436027	27094	7.206	0.136
Arias & Brown, 2009: 1074	Colombia	2003	630	213104	11651	0.338	0.018

6.5 Summary of cost

NBSwt are generally applied for secondary and tertiary treatment processes. NBSwt should be coupled with primary treatment for comprehensive water purification. The economic feasibility of primary treatment varies based on the geographical location and the scale of the facility. For instance, the construction cost of primary treatment facilities in Poland is estimated at 1.02 EUR/m^3/year (Beerbeka et al., 2012), while a more recent study in Turkey suggests a significantly lower construction cost of 0.01361

EUR/m³/year (Ozgun et al., 2021). Additionally, the maintenance cost in Turkey is reported to be 0.0115 EUR/m³/year (Ozgun et al., 2021). These figures are based on empirical data from 16 facilities in Turkey and 70 facilities in Poland, offering a comparative perspective on the economic aspects of primary treatment.

The review tables on construction and maintenance costs for different types of Nature-Based Solutions for water treatment—such as free surface water, horizontal flow, vertical flow, and hybrid systems—reveal a range of cost estimates. These variations can be attributed to several factors. Construction costs, for instance, could vary due to differences in labor costs, material prices, and the level of expertise required for specialized technologies. Inclusion or exclusion of site preparation, land acquisition, and permitting fees also contribute to disparate numbers. Maintenance costs, on the other hand, could encompass routine inspections, material replacements, labor, and ongoing monitoring, and these elements could differ in frequency and complexity depending on the type of NBSwt. Regional variations in labor and material costs further add to the variability. Understanding these underlying components is crucial for a nuanced economic assessment, especially when calculating land opportunity costs for competing land uses.

In table 10 the median costs for free surface water (FW), horizontal flow (HF), vertical flow (VF), and hybrid systems are presented based on the cost measures provided in table 6,7,8,9. The table reveals notable disparities in cost across these NBSwt. In terms of construction costs per flow measured in m^3/year, FF systems are the most expensive at 14 EUR, followed by hybrid systems at 9.8 EUR, VF at 3.7 EUR, and FW being the most economical at 0.5 EUR. Maintenance costs per flow also vary, with hybrid systems being the most costly at 0.24 EUR, and FW the least at 0.027 EUR. Both HF and VF have identical maintenance costs of 0.13 EUR. Intriguingly, despite HF and VF having the same maintenance costs, their construction costs differ significantly. Furthermore, the size per flow - measured in m^2/ ~ m^3 /year - ranges from 0.03 for VF to 0.07 for FW and HF, indicating varying land use requirements. These cost and size variations underscore the importance of careful selection and economic assessment when considering different NBSwt options. Furthermore, these measures are expressed in flow and not water treatment efficiency which is an important distinction and will be treated at length in the following chapter

Table 10 - Summary of cost estimates

	Construction cost in EUR per flow measured in m^3/year	maintenance cost in EUR per flow measured in m^3/year	size per flow m^2~m^3/year
FWS	0.5	0.027	0.07
HF	14	0.13	0.07
VF	3.7	0.13	0.03
Hybrid	9.8	0.24	0.05

7.0 Benefits of Wastewater Treatment: A Dual Perspective

Wastewater treatment yields a range of benefits that can be broadly categorized into two: internal and external benefits of treated water. Internal benefits are those that are directly associated with the wastewater treatment process itself. A commonly used yardstick for measuring these benefits is to assess the gap between the operational costs and the present value of the anticipated revenue. This revenue is primarily generated from the sale of treated water. In this context, the internal benefit can be defined as the market valuation of the treated water within the local economy.

In contrast, external benefits—those that extend beyond the immediate process—are more intricate to quantify. These benefits resonate not just economically but also socially and environmentally. Unlike internal benefits, they are not easily priced or traded in the market, making their monetary valuation more challenging. This complexity necessitates a comprehensive analysis that takes into account various externalities, which are pivotal for calculating the net benefit of wastewater treatment.

The total benefit of water treatment is the aggregated internal and external benefits:

$$\boldsymbol{Total\ Benefit = Internal\ Benefit\ + External\ Benefit} \tag{5}$$

This framework sets the stage for a multi-faceted evaluation, including the use of the shadow price of water treatment, to quantify these benefits comprehensively.

Wastewater treatment is fundamentally a process characterized by the removal of contaminants, pollutants, and impurities from wastewater, rendering it suitable for safe disposal or potential reuse. This process assumes paramount importance in upholding the cleanliness and sustainability of water resources, thereby safeguarding both human health and the environment. The contaminants extracted from wastewater are categorized as undesirable outputs, primarily due to the potential adverse environmental consequences they pose if released indiscriminately. In essence, the benefits derived from wastewater treatment stem from the elimination of these contaminants, pollutants, and impurities from wastewater streams.

7.1 The shadow price of water treatment

The shadow price approach, first introduced by Färe et al. (1989), offers a valuable methodology for evaluating both the economic and environmental impacts of wastewater treatment. This approach employs what is known as a 'distance function,' which serves as an expanded version of traditional production functions. In simple terms, this distance function measures how far off a given wastewater treatment process is from an ideal, highly efficient process. This ideal process would be the most efficient in terms of resource use, minimizing negative outputs like pollution, and maximizing positive outputs like clean water.

The concept of distance in this context refers to the efficiency gap between the current wastewater treatment process and an "ideal" or "optimal" process. The ideal process is essentially a theoretical construct representing the most efficient use of resources to achieve a given level of wastewater treatment. It's not just about what technology can achieve; it's about what we could achieve if we used resources in the most effective way possible, considering both economic and environmental aspects.

In economic terms, the distance represents an "opportunity cost," which is a measure of what society must give up in terms of alternative uses of the resources employed. For example, if we could achieve the same water quality with fewer resources (like energy, chemicals, or labor), then the saved resources could be employed elsewhere in the economy—perhaps for education, healthcare, or other environmental projects.

When we assign an economic value to this distance or opportunity cost, we get the shadow price. The shadow price reflects the true societal cost of wastewater treatment, capturing both direct costs and the value of foregone opportunities. Therefore, it can be seen as an expression of what society might be willing to pay for wastewater treatment if all costs and benefits were fully accounted for.

In a policy context, if the shadow price is high, it signals that society could potentially gain a lot by moving towards more efficient wastewater treatment processes. On the other hand, a low shadow price could indicate that the existing process is already efficient in societal terms, and there might not be significant gains from reallocating resources. The shadow price using a distance function is calculated in the following way:

- Initially, the wastewater treatment process under evaluation is thoroughly described, encapsulating elements such as employed technologies, operational scale, and water quality output.
- A mathematical model, known as the distance function, is then formulated. This function measures the efficiency of the wastewater treatment process by quantifying its divergence from a theoretically ideal, highly efficient system. Factors integrated into this function typically encompass variables like energy consumption, chemical inputs, and labor costs.
- Subsequently, resource utilization efficiency is assessed using the distance function. Here, the focus is on determining the quantity of various inputs required to transform a unit volume of wastewater into a treated state, as compared to what would be required in an idealized process.
- An economic valuation is then attributed to the identified efficiency gap. This valuation incorporates both the direct financial costs and the opportunity costs—representing the foregone benefits of alternative resource allocations.
- The final step involves calculating the shadow price itself, achieved by dividing the economic value of the efficiency gap by the volume of wastewater treated. This shadow price per cubic meter captures the comprehensive economic cost of wastewater treatment, accommodating both market and non-market considerations.

By examining these dimensions, the shadow price approach offers a comprehensive assessment that goes beyond mere cost analysis. It includes the societal and environmental impacts, or 'external benefits,' of wastewater treatment. This methodology has been validated through its application in various studies, such as those by Hernández-Sancho et al. (2010), Molinos-Senante et al. (2010), and Yeo et al. (2022).

It is important to note that calculating shadow prices using the distance function is just one approach among many possible methods. Other methods might involve contingent valuation surveys, hedonic pricing, or production function analysis, depending on the specific context and available data.

7.2 Internal benefits

The concept of direct benefits is predicated on the scarcity of water or, at the very least, on the proposition that treated water from these facilities will be supplied to users at a cost lower than existing alternatives. According to a study by Biekens et al. (2019), the average shadow price for irrigation water in semi-arid regions stands at 0.04 EUR/m³ for wheat production and 0.14 EUR/m³ for maize production. A comprehensive literature review conducted by the same authors reveals that shadow prices can range from 0.01 EUR/m³ to 0.24 EUR/m³, with an average value of approximately 0.1 EUR/m³. Conversely, in regions without water scarcity and where groundwater stocks are abundant, the cost of irrigation water—and, by extension, the direct benefit of treated water - would be substantially lower. In scenarios where the treated water is not put to any specific use - such as being discharged into oceans or river systems - the direct benefit could effectively be zero.

7.3 The indirect benefits

For indirect benefits, we can use the shadow prices of the different undesirable outputs such as nitrogen (N), phosphorus (P), suspended solids (SS), and organic matter that is measured as biological oxygen demand (BOD) and chemical oxygen demand (COD).

Table 11 shows the shadow prices of pollutants in different water destinations (rivers, seas, wetlands, and reuse) from Hernández-Sancho et al. (2010). Shadow prices are used to represent the cost of the environmental damage that would occur if the resource or service were not protected or provided. The shadow prices of pollutants in Table 11 vary depending on the pollutant and the destination of the water. For example, the shadow price of nitrogen (N) is highest in wetlands (65.209 EUR/kg), followed by reuse (26.182 EUR/kg), rivers (16.353 EUR/kg), and the sea (4.612 EUR/kg). This is because wetlands are particularly sensitive to N pollution, and N pollution can have a significant impact on the ecosystem services that wetlands provide.

Table 11 - shadow prices of pollutants (from Hernández-Sancho et al., 2010)

Destination	Reference price water EUR/m^3	Shadow prices for pollutants (EUR/kg)				
		N	P	SS	BOD	COD
River	0.7	16.353	30.944	0.005	0.033	0.098
Sea	0.1	4.612	7.533	0.001	0.005	0.010
Wetlands	0.9	65.209	103.424	0.010	0.117	0.122
Reuse	1.5	26.182	79.268	0.010	0.058	0.140

Concentrations of various pollutants such as Nitrogen (N), Phosphorus (P), Suspended Solids (SS), Biological Oxygen Demand (BOD), and Chemical Oxygen Demand (COD) can vary significantly in wastewater - see Table 12. Mean concentration values, expressed in milligrams per liter (mg/L), serve as a reliable indicator of the typical pollutant levels encountered. Additionally, the span of observed concentration values provides insights into the range of variability that is often seen in actual wastewater samples. A particularly important aspect of understanding these concentrations is the conversion factor provided for each pollutant, denoted in kilograms per cubic meter (kg/m^3). This conversion factor plays a critical role in quantifying the aggregate amount of pollutants that different Nature-Based Solutions for wastewater treatment are capable of mitigating.

Table 12 – Pollutant concentrations in municipal wastewater

Pollutant	Mean values (mg/L)	Range	Amount (kg/m^3)
N	70	40 - 100	0.07
P	18	14 – 22	0.018
SS	300	250 – 600	0.3
BOD	300	200 – 400	0.3
COD	700	400 – 1000	0.7

*Numbers provided by Dr. Pedro Carvalho

Nature-based solutions for wastewater treatment demonstrate varying degrees of treatment efficiency. Treatment efficiency is quantified in terms of percentages, representing the capability of each system to remove key pollutants like Nitrogen (N), Phosphorus (P), Suspended Solids (SS), Biological Oxygen Demand (BOD), and Chemical Oxygen Demand (COD). These efficiency metrics serve as valuable indicators for gauging the effectiveness of different NBSwt systems in reducing specific pollutants. Such quantifiable measures are crucial for calculating the total amount of pollutants mitigated, which is integral to assessing the environmental benefits of these wastewater treatment solutions — see Table 13.

Table 13 - Treatment efficiency of different types of NBSwt (from Cross et al., 2021 and Vymazal, 2013)

NBSwt type	Efficiency (%)				
	N	P	SS	BOD	COD
Free water surface (FWS)	30–80	27–60	65–76	54	41–90
Horizontal-flow (HF)	30–50	10–50	75	65	60–80
Vertical-flow (VF)	20–40	10–35	80–90	83	70–90
Hybrid (HB)	57.7	64.5	89-99.8	88	98.6-99

7.4 Treatment and Pollutant Removal Capacities in NBSwt Systems

The capacity to quantify treatment effects in NBSwt is fundamental for their evaluation and optimization. NBSwt capacity for pollutant removal can be determined by two key variables: the efficiency of the NBSwt system in removing individual pollutants and the concentration of those pollutants in the wastewater.

Mathematically, this is expressed as:

Pollutant removed (kg/year) = NBSwt flow (m^3/year) × Amount of pollutant in wastewater (kg/m^3) × Treatment efficiency (%) (6)

Using this model, we have derived the median treatment and pollutant removal capacities for the four NBSwt types. The median treatment capacity ranges from 11,000 m^3 for horizontal flow constructed wetlands (HF) to an impressive 5,524,000 m^3 for free water surface wetlands (FWS). These calculated capacities are comprehensively presented in Table 14, serving as an invaluable resource for assessing the environmental benefits and adaptability of different NBSwt systems.

Table 14 - Amount of pollutants removed (kg/year)

NBSwt type	Median treatment capacity (m^3)	Pollutants removed (kg/year)				
		N	P	SS	BOD	COD
FWS	5,524,000	212,674	43,253	1,168,326	894,888	2,532,754
HF	11,000	308	59	2,475	2,145	5,390
VF	43,500	914	176	11,093	10,832	24,360
HB	38,000	1,535	441	10,762	10,032	26,281

The environmental benefits of NBSwt can be quantified through the use of shadow prices, as delineated in the work of Hernández-Sancho et al. (2010). This enables the translation of pollutant removal into economic value, as expressed by the following equation:

Environmental benefits (EUR/year)=Shadow prices (EUR/kg)×Pollutant removed (kg/year) (7)

The equation has been used to calculate the monetary value of avoided environmental damage in terms of EUR per year for the median FWS, HF, VF, and HB NBSwt - see Table 15. The table highlights the significant environmental advantages offered by various NBSwt systems. For example, the median FWS has the potential to prevent environmental damage to the tune of 8.6 million EUR annually. In contrast, Horizontal Flow HF systems can mitigate harm up to 12.5 thousand EUR per year. The scale of these benefits varies, depending mainly on the median size of the specific type of NBSwt and the efficiency of pollutant removal. Of particular note is the outsized contribution of nitrogen and phosphorus removal to the overall prevention of environmental damage.

Table 15 - Environmental benefits (EUR/year)

NBSwt type	Avoided environmental damage (EUR/year)

	N	P	SS	BOD	COD	**Total**
FWS	5,973,800	2,391,551	7,594	47,653	234,280	**8,654,878**
HF	8,651	3,284	16	114	499	**12,565**
VF	25,659	9,741	72	577	2,253	**38,303**
HB	43,112	24,394	70	534	2,431	**70,541**

8.0 Cost-Benefit Analysis

This section aims to provide a rigorous and nuanced understanding of the economic viability and environmental efficacy of four distinct types of Nature-Based Solutions for wastewater treatment (NBSwt) - Free Water Surface (FWS), Horizontal Flow (HF), Vertical Flow (VF), and Hybrid systems. Specifically, we will conduct a comprehensive Cost-Benefit Analysis (CBA) for systems with a flow capacity of 10,000 m^3/year. The CBA integrates key economic metrics, such as construction and maintenance costs, and land opportunity costs as a function of spatial requirements, along with the monetized benefits of water treatment. To account for the time value of money, we employ a discount rate of 3% over a 40-year operational period.

One of the foundational elements in our Cost-Benefit Analysis is the evaluation of land opportunity costs for implementing the four types of Nature-Based Solutions for wastewater treatment: FWS, HF, VF, and Hybrid systems. These costs have been estimated using the land use models previously provided in this report. The results reveal substantial variations in land opportunity costs across different landscape settings - Urban, Suburb, Rural, and Farmland. For instance, in urban settings, the land opportunity cost for FWS and HF is considerably high at 540,280 EUR, reflecting the premium on land in densely populated areas. Conversely, the cost significantly drops to 1,680 EUR for farmland settings. VF generally requires less land, resulting in lower opportunity costs across all landscapes, with the cost being as low as 720 EUR in farmland. Hybrid systems present a middle-ground, with costs ranging from 1,120 EUR in farmland to 382,107 EUR in urban areas. These findings underscore the importance of considering the local land value context when selecting an NBSwt system.

Table 16 - Land opportunity cost for a facility with a capacity of 10000 m^3 per year

	Landuse cost in EUR			
	Urban	Suburb	Rural	Farmland
FW	540280	227586	69876	1680
HF	540280	227586	69876	1680
VF	223935	168907	50489	720
Hybrid	382107	198246	60182	1120

* Note that FW and HF is assessed to take up equal amount of space according to sources provided in section 6.

The NPV results of the CBA reveal interesting insights into the economic viability of different NBSwt types under various land opportunity cost scenarios - see Table 17. When implemented in urban settings, all NBSwt types yield a negative NPV, emphasizing the critical role of land opportunity costs in determining the feasibility of such projects. Free Water Surface (FWS) wetlands emerge as the most favorable option with positive NPVs in all settings except urban. This is attributable to their lower construction and maintenance costs. Interestingly, despite its efficiency in pollutant removal, the Hybrid system (HB) has a relatively lower median NPV, partially owing to its higher costs. Vertical Flow (VF) solutions, while not the most economical, offer the added advantage of being submergible, thus allowing for other types of land use above ground and making the solution somewhat insensitive to land opportunity cost. Also, note that the land-opportunity cost is specific to a Danish setting, and therefore results might differ in other regions in the world with a larger supply of land and lower land-use competition. The direct benefit of treated water potential as irrigation was also not included in the analysis. Still, FWS appears to be the most viable option, especially in lower land cost scenarios like rural and farmland settings, with a median NPV of 110,480 EUR.

Table 17 - Net present value of different treatment facilities (with a capacity of 10,000 m^3)

	Land opportunity cost scenarios in EUR				
NBSwt type	Urban	Suburb	Rural	Farmland	Median
FWS	-281,068	31,625	189,335	257,531	110,480
HF	-506,588	-193,894	-36,184	257,531	110,480
VF	-132,152	-77,124	41,293	91,062	110,480
HB	-202,759	-18,898	119,165	178,227	50,133

9.0 Discussion

The primary objective of this report has been to explore the economic viability of NBSwt. The report has delved into the challenges and opportunities presented by NBSwt, examining their potential for cost savings, environmental benefits, and societal impact. It has also provided a robust economic assessment framework through comprehensive cost-benefit analyses to guide decision-makers in choosing effective water treatment strategies. The purpose of this discussion section is to synthesize these findings, evaluate their implications in the broader context of environmental economics and policy, and offer insights for future research and implementation.

In this report, we have presented a multi-faceted analysis that delves into the economic aspects of NBSwt. Our findings reveal that the construction and maintenance costs of various NBSwt systems—namely free water surface, horizontal flow, vertical flow, and hybrid systems—vary significantly, offering a range of options for different budget constraints. Importantly, we introduce a novel pathway for assessing land opportunity costs, which serves as a critical factor in determining the landscapes where NBSwt can be feasibly implemented. This is particularly relevant in densely populated or high-value land areas where land opportunity costs could be a restricting factor. Further enriching the economic perspective, we provide valuable insights into the internal benefits of using treated water for irrigation, as well as the external benefits of water treatment and removal of pollutants calculated through shadow prices derived from distance functions. These benefits not only add layers of value to NBSwt but also contribute to broader environmental and social goals. By integrating these diverse sets of data, we offer a comprehensive cost-benefit analysis framework that equips analysts and decision-makers with the foundational knowledge needed to make economically efficient choices in water treatment strategies.

Our work stands as a novel contribution to the research field that focuses on nature-based solutions, particularly in the economic assessment of nature-based solutions for water treatment (NBSwt). While previous studies have primarily focused on case-specific information, lacking a generalized approach, our report takes a pioneering step by offering comprehensive building blocks for the cost-benefit analysis (CBA) of NBSwt systems. This framework synthesizes a wide array of economic factors, from construction and maintenance costs to land opportunity costs and the valuation of internal and external benefits. By doing so, we provide analysts and decision-makers with a robust, adaptable tool that can be applied across various contexts and scales. This is a significant advancement over existing literature, which has largely been confined to isolated case studies that offer limited scope for broader application. Our approach not only fills a critical gap in the literature but also sets the stage for more informed and economically efficient decisions in the realm of water treatment solutions.

Our cost-benefit analysis reveals that all four types of NBSwt systems—free water surface, horizontal flow, vertical flow, and hybrid—can be economically viable, but their feasibility is highly dependent on the degree of urbanity and competition for space. Notably, the free water surface NBS emerged as the most economically promising, providing the highest average Net Present Value (NPV) across various landscapes, except for highly urbanized cityscapes. This suggests that the economic viability of NBSwt is closely tied to land opportunity costs. Cost-benefit analysis of NBSwt can vary significantly depending on regional factors such as demand for space, need for irrigation, and the shadow price associated with water treatment. Therefore, while our framework provides a generalized approach for conducting informative CBAs, it also allows for the incorporation of context-specific variables, making it a versatile tool for economic assessment in diverse settings.

The pilot projects associated with the MULTISOURCE report offer real-world applications that both validate and challenge our findings. For instance, the hybrid system at ICRA in Girona aligns well with our assessment that hybrid systems can be economically viable, particularly in specific urban settings. On the other hand, the phytoparking system at t' Hof Bellewaerde in Belgium presents an innovative approach that our current framework may not fully capture, suggesting the need for further refinement to accommodate such unique solutions. These pilot projects underscore the adaptability of NBSwt solutions but also highlight the importance of context-specific economic assessments. They serve as both a validation and a call for further refinement of our economic assessment framework for NBSwt.

While this report provides valuable insights into the economic viability of various NBSwt systems, it is important to acknowledge its limitations, as well as those of the studies it cites. One significant constraint is the reliance on cost estimates extracted from literature where the primary focus was not on construction or maintenance costs. These costs have likely been measured in different ways and could be influenced by regional variables such as labor costs, capital costs, resource costs, and the availability of specific competencies and skills.

Our approach is essentially a top-down assessment, which, while offering a broad overview, may lack the specificity required for individual projects. An alternative would be a bottom-up assessment, where costs are evaluated in detail for specific NBSwt systems. However, this approach also has its drawbacks, as it could produce results that are too specific and non-generalizable. Another area for improvement is the shadow price benefit assessment; making these values region-specific could enhance the precision of the CBA. Similarly, land use models estimating land opportunity costs could be developed on a global or regional scale for more accurate assessments. It's crucial to note that while the results of this report can serve as a useful starting point, providing ballpark estimates for scoping exercises, they are not intended to be precise or directly applicable to specific projects. Nonetheless, they offer an informative foundation for further, more detailed analysis.

10.0 References

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Appendix A: Descriptive statistic of the three cluster of land use

Descriptive Statistics Rural cluster					
Statistic	N	Mean	St. Dev.	Min	Max
price	3,067	94,902	99,647	3,900	3,250,000
size m2	3,067	1,007	352.848	135	2,999
address per km2	3,067	34	25	0.087	120
Descriptive Statistics surburbian cluster					
Statistic	N	Mean	St. Dev.	Min	Max
price	399	245,418	301,206	18,850	3,380,000
size m2	399	820	317	167	2,516
address per km2	399	208	93	124	645
Descriptive Statistics urban cluster					

Statistic	N	Mean	St. Dev.	Min	Max
price	31	593,949	316,888	194,350	1,677,000
size m2	31	752	336	314	1,964
address per km2	31	1,421	436	857	2,955

The overall goal of MULTISOURCE is to, together with local, national, and international stakeholders, demonstrate a variety of about Enhanced Natural Treatment Solutions (ENTS) treating a wide range of urban waters and to develop innovative tools, methods, and business models that support citywide planning and long-term operations and maintenance of nature-based solutions for water treatment, storage, and reuse in urban areas worldwide. The project includes seven pilots treating a wide range of urban waters. Two individual municipalities (Girona, Spain; Oslo, Norway), two metropolitan municipalities (Lyon, France; Milan, Italy), and international partners in Brazil, Vietnam, and the USA will contribute to each of the main project activities: ENTS pilots, risk assessment, business models, technology selection, and the MULTISOURCE Planning Platform. The use of urban archetypes in the Planning Platform will enable users to quickly classify regions (in both developed or developing countries) suitable for the application of nature-based solutions for water treatment (NBSWT) and compare scenarios both with and without NBSWT.

MULTISOURCE
enhanced natural treatment solutions

This project has received funding from the European Union’s Horizon H2020 innovation action programme under grant agreement 101003527.