

TIM ROBIN LORENZEN

**A NEW BIODEVICE WITH PLANTS AND LOCAL CORK
TO CONTROL WATER EUTROPHICATION IN URBAN
LAKES**



UNIVERSIDADE DO ALGARVE
Instituto Superior de Engenharia
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TO CONTROL WATER EUTROPHICATION IN URBAN
LAKES**

Mestrado em Ciclo Urbano da Água

Trabalho realizado sob a orientação de:

Prof. Doutora. Manuela Moreira da Silva, Instituto Superior de Engenharia da Universidade
do Algarve. CIMA-ARNET

Prof. Doutora Cristina Veiga Pires, Faculdade de Ciências e Tecnologia da Universidade do
Algarve. CIMA-ARNET



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Declaration of authorship of the work

I hereby declare to be the author of this work, which is original and unpublished. Authors and works consulted are properly cited in the text and included in the reference list.

(Tim Robin Lorenzen)

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ACKNOWLEDGEMENTS

The completion of this thesis marks the end of an intensive and educative phase of my life, which I would not have been able to master in this form without the support of many people. I want to take this opportunity to thank some of those who have accompanied and supported me along the way.

First, I'd like to thank my family for being the foundation of who I am today. So in order of appearance, I thank: Wiebke for supporting where she could, opening horizons and creating opportunities; Jule for her infinite & unconditional support, guidance through personal & academic life of inestimable personal value through so many moments full of joy and not-joy; Metin for being with us the way he is; Aleyna who "grew up so fast" and who makes me so proud every time I think of her; Pit for his significant role in my life and showing different perspectives and Melanie for always offering a listening ear and kind words.

My deepest gratitude goes to the most important person I met during my master's degree, Beatriz. Your support and patience made all the difference along this journey. It is a team achievement, with many more to follow.

Von Herzen vielen Dank for their hands-on support with this thesis to Exzellenz-Uli, Designguru Leon and Genosse Felix.

I can assure the rest of my friends, who are not mentioned by name for reasons of space, that there is a special place for them too and that I am still happy about the numerous and extensive visits to the Algarve! Muito obrigado to my Faro folks for (work) shelter, (business) support, laughter and countless amazing memories. Friendships endure over time.

For supporting my professional career, I thank Regina & Claus from the GFZ Potsdam for their trust and support during my internship, an experience that continues to shape my personal and professional growth. Gratitude also goes to Petra and André at argusim Umwelt Consult for their support during my B.Sc. and beyond.

Last but certainly not least, I want to thank almost everybody involved in this dissertation for their help, guidance and input.

RESUMO

A demografia e a sócioeconomia das últimas décadas têm alterado o funcionamento dos recursos aquáticos, gerando entre outras consequências, eutrofização com consequente destruição de habitats, perda de biodiversidade e riscos para a saúde pública. Este trabalho de ecologia urbana, procurou desenvolver uma Solução Baseada na Natureza (NbS) para melhorar o estado ecológico de um lago urbano, através de espécies macrófitas autóctones. fitorremediadoras de nutrientes na água. Pretendeu-se contribuir para melhorar o funcionamento do lago do Jardim das Comunidades – Almancil, Loulé, no âmbito de um projeto de investigação sobre a performance ambiental deste espaço urbano, do Instituto Superior de Engenharia - Universidade do Algarve e do Município de Loulé. Os protótipos do biodispositivo foram construídos com peças de cortiça, do interior de Loulé - Algarve, ligadas entre si com corda náutica, e onde se abriram orifícios para colocar exemplares de *Typha latifolia*, *Phragmites australis* e *Juncus inflexus*, selecionadas pela sua capacidade de fitorremediação. Caracterizou-se a cortiça (cor, textura, densidade e espessura) e avaliou-se o funcionamento do biodispositivo, com monitorização da qualidade da água do lago quantificando-se amónia, nitritos, nitratos, azoto total, fosfatos, fósforo total, clorofila *a*, oxigénio dissolvido, temperatura, pH e transparência ao Disco Secchi, antes e depois da sua instalação. Classificou-se o estado ecológico do lago através de um Índice de Estado Trófico (IET). Entre junho de 2022 e junho de 2023, não houve episódios de eutrofização, o biodevice terá contribuído para reduzir as concentrações de nutrientes na água, de $0,021 \pm 0,007$ para $0,002 \pm 0,001$ mg/L PO₄, e de $0,050 \pm 0,007$ para $0,020 \pm 0,006$ mg/L NH₄. A clorofila *a* manteve-se entre $4,00 \pm 0,79$ mg/m³ em junho de 2022 e $4,87 \pm 0,20$ mg/m³ em junho de 2023. A introdução indevida de espécimes presumivelmente exóticos de tartarugas e peixes no lago contribuiu para o aumento do azoto e do fósforo na água, dificultando a interpretação dos resultados obtidos. O azoto total aumentou de $1,59 \pm 0,21$ mg/L N para $68,05 \pm 8,85$ mg/L N, e por isso o IET (de 62,4 para 126). O fósforo total também aumentou de $0,03 \pm 0,005$ mg/L P para $0,08 \pm 0,009$ mg/L P, portanto, o IET passou de 37,4 para 53,3. Estes exemplares exóticos devem ser retirados e o biodevice deve continuar a ser testado, assegurando-se em simultâneo as condições hidrodinâmicas já definidas como ideais para o lago. Na construção do biodispositivo, deve ser testada outra corda que seja resistente à água e tenha uma pegada ecológica mais baixa.

Palavras Chave: Ecologia Urbana; Espécies Macrófitas; Cortiça; Soluções Baseadas na Natureza; Cidades Mediterrânicas.

ABSTRACT

The demographics and socio-economics of recent decades have altered the functioning of aquatic resources, generating, among other consequences, eutrophication with the consequent destruction of habitats, loss of biodiversity and risks to public health. This work on urban ecohydrology sought to develop a Nature-Based Solution (NbS) to improve the ecological status of an urban lake, using native macrophyte species that are phytoremediators of nutrients in the water. The aim was to help improve the functioning of the lake at Jardim das Comunidades - Almancil, Loulé, as part of a research project on the environmental performance of this urban space, organised by the Instituto Superior de Engenharia - Universidade do Algarve and the Loulé municipality. The prototypes of the bio-device were built with pieces of cork from the interior of Loulé - Algarve, connected to each other with nautical rope, in which holes were drilled to place specimens of *Typha latifolia*, *Phragmites australis* and *Juncus inflexus*, selected for their phytoremediation capacity. The cork was characterised (colour, texture, density and thickness) and the functioning of the biodevice was assessed by monitoring the lake's water quality, quantifying ammonia, nitrites, nitrates, total nitrogen, phosphates, total phosphorus, chlorophyll *a*, dissolved oxygen, temperature, pH and Secchi disk transparency before and after its installation. The ecological status of the lake was classified using a Trophic State Index (TSI). Between June 2022 and June 2023 there were no eutrophication episodes, the biodevice is considered to have contributed to the reduction of nutrient concentrations in the water from 0.021 ± 0.007 to 0.002 ± 0.001 mg/L PO₄ and from 0.050 ± 0.007 to 0.020 ± 0.006 mg/L NH₄. Chlorophyll *a* remained between 4.00 ± 0.79 mg/m³ in June 2022 and 4.87 ± 0.20 mg/m³ in June 2023. The improper introduction of presumably exotic specimens of turtles and fish into the lake contributed to the increase in nitrogen and phosphorus in the water, making it difficult to interpret the results obtained. Total nitrogen increased from 1.59 ± 0.21 mg/L N to 68.05 ± 8.85 mg/L N, and the TSI from 62.4 to 126. Total phosphorus also increased from 0.03 ± 0.005 mg/L P to 0.08 ± 0.009 mg/L P, so the TSI rose from 37.4 to 53.3. The exotic specimens should be removed and the biodevice should continue to be tested, while ensuring the hydrodynamic conditions already defined as ideal for the lake. In the construction of the biodevice, another rope should be tested that is water-resistant and has a lower ecological footprint.

Keywords: Phytoremediation; Eutrophication; Constructed Floating Wetland (CFW); Nature-based Solutions (NbS); Macrophyte vegetation

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LIST OF ACRONYMS

C	Carbon
CFW	Constructed Floating Wetlands
Chl-a	Chlorophyll <i>a</i>
CIE	Commission Internationale de l'Eclairage (International Commission on Illumination)
CO₂	Carbon Dioxide
D65	Daylight 6500K (Standard Illuminant)
DES	Department of Environment and Science
DO	Dissolved Oxygen
g/cm³	Grams per Cubic Centimetre
GI	Green Infrastructure
IPMA	Portuguese Institute for Sea and Atmosphere
ISE-UAlg	Institute of Engineering - University of the Algarve
IWRM	Integrated Water Resources Management
kg	Kilogram
kN	Kilonewton
LQ	Limit of Quantification
m²	Square Meter
m³/h	Cubic Meters per Hour
Mg	Megagram (Metric Ton)
mg/L	Milligrams per Liter
mg.m⁻³	Milligrams per Cubic Meter
N	Nitrogen (elemental symbol)
NbS	Nature-based Solutions
NH₄	Ammonium
NNE	North-Northeast
NO₂	Nitrite
NO₃	Nitrate
P	Phosphorus (elemental symbol)
pH	Potential of Hydrogen (Acidity/Basicity)

PO₄	Orthophosphate
PVC	Polyvinyl Chloride
RO	Research Objective
SD	Standard Deviation
SDGs	Sustainable Development Goals
SSW	South-Southwest
TN	Total Nitrogen
TP	Total Phosphorus
TSI	Trophic State Index
UAlg	University of Algarve
UNDESA	United Nations Department of Economic and Social Affairs
UN	United Nations
USA	United States of America
WWTP	Wastewater Treatment Plant
WSUD	Water Sensitive Urban Design
µg/L	Micrograms per Liter

1

INTRODUCTION

The effects of climate change are becoming increasingly tangible for people all around the world. Many of them are associated with water resources, such as droughts (Pokhrel *et al.*, 2021), floods (Tabari, 2020) and impaired quality (Rocha *et al.*, 2020). In response to these emerging challenges, ensuring the “*availability and sustainable management of water and sanitation for all*” is stated as one of the 17 Sustainable Development Goals (SDGs) in which the United Nations (UN) set the agenda for worldwide economic, social and environmental transformation for “*people, planet and prosperity*” until 2030 (United Nations General Assembly, 2015).

The necessity of good management of the available resources and the need for ongoing innovation becomes especially clear when looking at the growing world population numbers and the immense (ongoing) increase of people living in cities (United Nations Department of Economic and Social Affairs, Population Division, 2022).

While classical grey infrastructure was predominant when it came to water management in those urban areas for a long time now a shift towards integrating green infrastructure (GI) has been witnessed for a few decades (Jørgensen, 2016; Oral *et al.*, 2020). Nature-based Solutions (NbS) can be specific measures or actions implemented within a GI framework. They provide a set of tools which use natural processes to address societal challenges often connected with water management.

This dissertation aims at showcasing the development of a biodevice that is designed to improve the water quality of a city park lake in southern Portugal using locally sourced material (cork) and autochthonous vegetation. The biodevice is an artificial island (also called constructed floating wetland (CFW)) and uses phytoremediation to remediate eutrophication

problems. This study depicts its development, construction process and possible designs before assessing the results of an *in-situ* test phase. The project under which the study took place is a cooperation between the Institute of Engineering - University of the Algarve (ISE-UAlg) and the municipality of Loulé.

The following pages will give a brief description of the objectives of the project and its context of origin before giving a more detailed overview of the rest of the dissertation.

1.1 OBJECTIVES AND CHARACTERISTICS OF THE PROJECT

The present research project of urban ecohydrology aims to assess the feasibility of using Nature-based Solutions to improve the quality of urban water bodies, specifically through phytoremediation via a biodevice that employs autochthonous macrophytes placed on cork boards as floating material.

To meet this target the following research objectives (ROs) have been formulated:

RO 1: Develop prototypes for phytoremediation of nutrients from urban water bodies to improve its ecological status - specifically to prevent eutrophication - by utilizing cork from the Algarve and autochthonous macrophytes.

RO 2: Test the prototypes in the lake of Jardim das Comunidades – Almancil.

RO 3: Disseminate the idea of the prototype to other municipalities by creating a short flyer for a non-scientific audience.

From which initial situation and in which context these objectives emerged is briefly described in the next subchapter.

1.2 CONTEXT OF THE WORK

This work was developed as part of a collaborative project of the Institute of Engineering - University of the Algarve (ISE-UAlg) in partnership with the Municipality of Loulé and the CIMA Research Centre. The project aims at increasing scientific knowledge about the ecosystem services provided by the Jardim das Comunidades - Almancil (Portugal) to the surrounding community, and to improve the environmental performance of this public green space. The further objective of the overarching project is to contribute to people's quality of life and improve local resilience to climate change.

Local press summarizes it with: *“The Garden of Communities of Almancil has been the target of several interventions with a view to improving water and energy management and*

enhancing its ecosystem services, namely its carbon sequestration capacity” (Sul Informação, 2021).

Parts of the project are interventions to improve the water quality of the city’s park centre piece, an artificial lake with ongoing eutrophication problems. The study activities of monitoring the lake led to technological and non-technological measures to improve water quality keeping in mind the key principles of the Water Sensitive City concept.

The project, which is part of the brand ‘Loulé adapta’ (a set of climate adaption measures) created by the municipality of Loulé, has led to several dissertations from students of the master course Urban Water Cycle at the ISE-UAAlg. This dissertation is one of them.

The following sections provide a detailed overview of the structural organization of this thesis.

1.3 ORGANIZATION OF THE THESIS

This thesis is organized into five chapters, one bibliographic references section and some appendices.

In the first chapter, a very short framework of the main research problem under investigation is presented to underline the relevance of the work.

The second chapter will guide the reader into the state-of-the-art literature on the different subjects that represent the conceptual baseline and knowledge of the present work, namely, sustainable water management in cities, Nature-based Solutions, phytoremediation, macrophyte vegetation, nitrogen and phosphorus cycle in lakes and finally on innovative solutions in the urban water cycle.

The third chapter will then present the case study, detailing the physical and morphological specificities of the study site, the genesis of the prototype and the methodologies used to assess water quality (including methodological constraints) and cork characterization. It also presents the chosen species and their rationale, mainly having high phytoremediation capacity. The last subchapter of the third part explains the construction process with great detail which is important to potentially reproduce the concept of the biodevice once disseminated following RO3.

The fourth chapter presents the results of the different assessed parameters for water quality and cork characterization, carries out analyses, shows four different design variants which are all based on the same principle and provides a detailed discussion about the previous points. The development of the water quality analyses is based on limnological parameters as well as a trophic index and considers influencing factors such as the introduction of potentially exotic

fauna. The contents of an information flyer about the biodevice are presented and explained. The concluding discussion evaluates the findings.

The core part of the dissertation is concluded by the fifth chapter which summarises the key findings and outlines prospects for future research.

The penultimate part of the work is the bibliographic references section, which was kept in APA citation style.

The very last part of the thesis is the appendices, which contain additional information, illustrations and further details. These supplement the central content and provide background material that is relevant for the comprehensibility of the work.

2

LITERATURE REVIEW

The present work is based on several concepts and previous works developed that are presented in the following paragraphs, starting from the sustainable water management in cities framework, going to the concept of Nature-based Solutions before explaining phytoremediation and the macrophyte vegetation by which it is performed in this study. This part of the work also explains the basics of the aquatic nutrient cycle of the two most important nutrients nitrogen and phosphorus. The last part of this chapter builds the conceptual bridge to the development of the biodevice developed in this study as one of many innovative solutions in urban water cycles.

2.1 SUSTAINABLE WATER MANAGEMENT IN CITIES

Even though only around two percent of the world's land surface is covered by urban areas (International Resource Panel, 2018; UN-Habitat, 2022), over 50% of the worldwide population lives in them (United Nations Department of Economic and Social Affairs, Population Division [UNDESA], 2019). According to the UN Department of Economic and Social Affairs, urbanization is a “*demographic mega-trend*” and is expected to increase to 68% of the world’s population living in urban areas (UNDESA, 2019). As shown in Figure 1 the biggest growth is projected for Asia and Africa, but also European cities are expected to grow further.

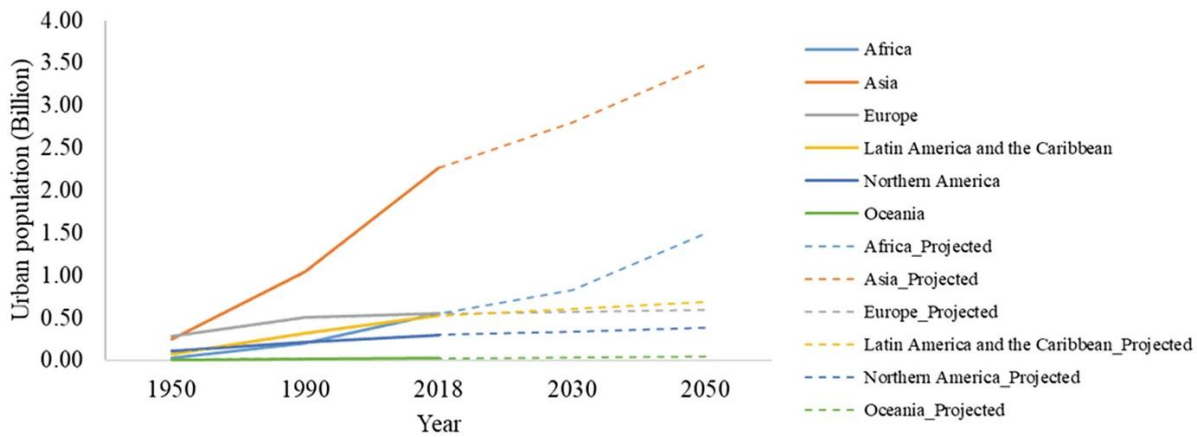


Figure 1. Urban population projection by 2050 (Ganapathi *et al.*, 2024).

One of the SDG's 17 goals is also dedicated to cities: “*Make cities and human settlements inclusive, safe, resilient and sustainable*” (United Nations General Assembly, 2015). UNDESA (2019) states that sustainable urban development must be aiming at providing water/ sanitation infrastructure and “*preserve a healthy environment within the city and surrounding areas*”. The described growth also means that cities are becoming more important when it comes to water challenges (Grison *et al.*, 2023).

Public urban entities are responsible for the management of space and natural resources and therefore have the power and the obligation to work towards sustainable solutions (Grison *et al.*, 2023). This can mean creating awareness among city dwellers, especially the younger generations since they are going to be the most affected by climate change (Moreira Da Silva *et al.*, 2024). Furthermore, the public sector has the potential to become a sustainability role model and inspire other sectors and organizations to follow suit (Cusumano & Vecchi, 2022). There are several different concepts, each with its specific angles and details when it comes to what exactly sustainable water management (in cities) means. Discussing all of these approaches in detail here would go beyond the scope of this paper. The next paragraphs should therefore be considered as a rough overview of some of the available concepts and frameworks that form the underlying principles of the developed biodevice.

Integrated water resources management (IWRM) is an inter-sectoral approach that takes into account social, economic and environmental considerations (Taylor, 2023). The concept can also but not only be applied to urban areas. Some of its key principles are recognizing the intrinsic value of water, ensuring the integration of water management across sectors, and adopting a holistic long-term perspective. IWRM seeks to address the complex challenges

associated with water scarcity, pollution, and climate change. It provides a framework for balancing competing water demands and promoting sustainable development (Taylor, 2023).

A set of “green tools” that can be used to achieve better IWRM is ecohydrology. Ecohydrology integrates hydrology and ecology for cost-effective solutions to environmental problems. Its early-mid 1970s emergence was influenced by the growth in public concern about pollution and the understanding of natural systems. Ecohydrology is a sub-discipline of ecological engineering dealing with environmental problems, including non-point pollution management using hydrological retention time and wetlands for buffering floods and enhancing carbon sequestration. It seeks to reduce the level of eutrophication in different ecosystems and finally assesses the overall influence of wetlands, lakes, and reservoirs on the climate. Ecohydrology also considers the importance of small ecosystems for the health of larger areas and the sustainability of ecosystems. It helps in maintaining ecosystem services by understanding and managing the hydrological cycles and addresses the impacts of climate change (Jørgensen, 2016).

The hydrological cycle involves the storage and movement of water through the hydrosphere, lithosphere, biosphere, and atmosphere. This cycle exists in natural environments, independent of human impact (Collier, 2016). Urbanization and other human-induced processes have altered the natural hydrological cycle. Researchers have therefore started to focus on the development of a classification called the urban water cycle. Growth in urban agglomerations, accompanied by the massive expansion in the construction of buildings and infrastructure increased soil sealing. This has caused severe changes to water flows (Oberndorfer *et al.*, 2007). The hydrological cycle is therefore altered by increased surface runoff due to the large number of buildings and impervious surfaces, but also by decreased evapotranspiration and infiltration in ecosystems altered by human activities (McGrane, 2016).

Water Sensitive Urban Design (WSUD) has the objective to mitigate the consequences of the altered natural water cycle in cities. WSUD therefore developed a set of management practices which aim at maintaining natural hydrology, protecting water quality, reducing stormwater runoff, and using green infrastructure to improve urban amenities. The main approaches can include the prevention of stormwater pollution through the preservation of waterways, the application of permeable pavements, and the setup of rainwater tanks. Stormwater can be captured by gully baskets, gross pollutant traps, vegetated swales, bioretention, rain gardens, and constructed wetlands. As stated in its name, Water Sensitive Urban Design is also concerned with aesthetic aspects of stormwater mitigation. Its practices

are means of sustainably managing (storm)water while enhancing urban aesthetics and addressing urban heat island and water quality issues (Hoban, 2019).

Figure 2. The integration of water resources in the natural-, the built-environment and WSUD areas. Figure 2 summarizes the natural, urban, and (ideally according to WSUD) alternated urban water cycle.

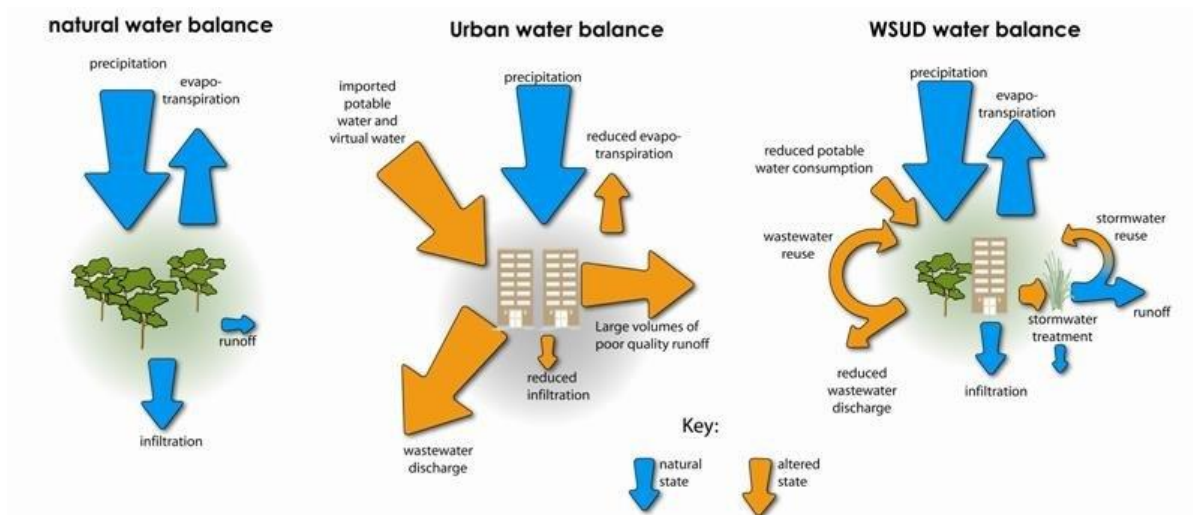


Figure 2. The integration of water resources in the natural-, the built-environment and WSUD areas (Hoban and Wong, 2006, as cited in Haywood, 2017).

The change towards an urban water cycle brings a variety of challenges. Each region has their own difficulties when it comes to sustainable urban water management and therefore requires their own set of solutions. From sinking cities due to decreasing groundwater levels like in Mexico City or Jakarta (Pattison & Cooke, 2024) via dams and dikes in the Netherlands (Tromp *et al.*, 2022) to long dry periods and too heavy precipitation events on the Iberian Peninsula (see for example Sánchez-García & Schulte, 2023).

In the present paper, the conditions in the Portuguese Algarve are decisive. The Algarve is one of the regions in Portugal with the least precipitation during the summer months but discontinuous and heavy rainfall events in winter which regularly cause flooding (Agência Portuguesa do Ambiente, I.P., 2020).

Not all water bodies in cities (solely) are natural or used as sweet water reservoirs. In the present case, the study took place on an artificial lake in the centre of a public park in Almancil (Jardim das Comunidades), a recreational area with a very central location. The park, especially the lake itself, provides a countermeasure against the heat island effect by providing a green space and the trees within the park sequesterate carbon from the atmosphere. Due to

problems that derive from the seasonal weather changes described and from other factors that will be described more closely in chapter 3.1, the lake has had problems with eutrophication since its construction. Although eutrophication can sometimes be observed for natural surface waterbodies, it is a central problem for artificial lakes (Zhao *et al.*, 2013) and is mostly connected to anthropogenic activity of some form (Hwang, 2020).

To tackle water problems in cities, more and more scientists pledge for more green and blue GI to replace or go along with classical grey infrastructure (e.g., Jørgensen, 2016; Liu & Jensen, 2018; Oral *et al.*, 2020). A deeper examination of innovative inventions in the urban water cycle will follow in chapter 2.6. For this study, the concept of Nature-based Solutions is certainly the most crucial one and will therefore be described further in the following section.

2.2 NATURE-BASED SOLUTIONS

Nature-based Solutions are developed to address a diverse range of environmental, social, and economic challenges by applying and enhancing natural processes. As part of the living infrastructure in urban areas, NbS can contribute to the quality of life by providing ecosystem services in multiple ways (Martín *et al.*, 2020). The two main integrated infrastructure types NbS consist of are blue and green infrastructure. The techniques of NbS encompass the sustainable management of urban areas, ecological functioning, and adaptation to cumulative climate change effects through enhancing urban resilience (Krauze & Wagner, 2019).

NbS that are integrated in urban settings operate on several functional levels. They can be part of critical infrastructure in natural disaster risk reduction, for example through rainwater flow buffering, carbon sequestration, and operating as phytoremediation mechanisms (Martín *et al.*, 2020). NbS also support ecosystem services including biodiversity conservation and green spaces providing valuable recreation opportunities. These attributes make NbS indispensable for municipal sustainable action (Kabisch *et al.*, 2022).

Strategic NbS placement in urban communities play an essential role in mitigating the effects of urban heat islands and in promoting urban liveability and ecological status. It may seem tempting to assume that implementing NBS, or green infrastructure, is always a promising idea in every urban context. However, the conditions which are favourable for implementing NbS require a comprehensive understanding of soil, climatic and hydrological conditions that may not be available or accessible in every case. In some contexts, failure to apply NbS in a location-specific manner could lead to an inappropriate choice of green

infrastructure, which could result in biodiversity loss or unwanted regime shift, while in other cases, for example in arid climates, the presence of urban NbS could disturb local water and nutrient cycles and potentially lead to fresh water scarcity (Martín *et al.*, 2020).

NbS cannot always function in the required manner unless the solution is hybridized with conventional engineering. Such a hybrid solution is one where natural elements are multi-functional components of a set-up that often work alongside and in union with, engineered ecosystems where concrete materials are used to improve the performance of NbS (Martín *et al.*, 2020). These approaches can be particularly important in high-density urban areas where space and resources are limited, and the necessity for infrastructure development is increasing. NbS are also often more cost-effective than classical grey infrastructure (Kabisch *et al.*, 2022).

It is therefore not surprising that the scientific field of NbS is under constant development (e.g., Calabrese *et al.*, 2023; Wickenberg, 2024). In connection with the renaturalization of the urban water cycle, NbS provide a wide array of ‘tools’ to mitigate and solve problems within urban water management (Stefanakis *et al.*, 2024).

Phytoremediation is one of the widely used and discussed techniques in the area of NbS (O’Connor *et al.*, 2019). As it is important to the understanding of the research project, its workings will be introduced in detail in the next subchapter.

2.3 PHYTOREMEDIATION

Phytoremediation is a sustainable green technology that uses plants to remediate a variety of pollutants and nutrients from contaminated water, soil and air. In the last decades, phytoremediation has received considerable attention as an eco-friendly option to replace or complement traditional engineering techniques of pollutant remediation (Li *et al.*, 2024; Pilon-Smits, 2005). Phytoremediation uses the natural features of specific plants helping to remediate pollution (often coming from human activities) (Ismail & Talebi, 2023). Choosing a plant species suitable for phytoremediation is essential for the success of a project since they need to be selected according to the specific problem that is being targeted (Agung Laksana *et al.*, 2023; Singh *et al.*, 2014; Zhou *et al.*, 2023).

Various phytoremediation methodologies are available for the removal of a wide variety of pollutants (Nedjimi, 2021). A brief overview of the different phytoremediation technologies can be seen in Table 1.

Table 1. Kinds of phytoremediation (taken from Vamerali *et al.*, 2010)

Technology	Description
Phytoextraction	Uptake of pollutants from environment and their concentration in harvestable plant biomass
Phytostabilisation	Reduction of mobility and bioavailability of pollutants in environment
Phytovolatilisation	Removal of pollutants from soil or water and their release into air, sometimes as a result of phytotransformation to more volatile and/or less polluting substances
Phytotransformation	Chemical modification of pollutants as a result of plant metabolism, both in planta and ex planta, often resulting in their inactivation, degradation (phytodegradation) or immobilisation (phytostabilisation)
Rhizofiltration	Use of plant roots to absorb and adsorb pollutants or nutrients from water and wastewater (e.g. buffer strips)

Kristanti & Hadibarata (2023) reported that aquatic plants have emerged as an attractive tool for remediation of both organic and inorganic contaminants from polluted waters. There are different scenarios in which phytoremediation through aquatic plants is being used with the remediation of heavy metals seeming to be a widespread thematic (Delgado-González *et al.*, 2021). More applications of the “power of plants” in this context can be found in stormwater treatment (as part of green infrastructure) (Mohsin *et al.*, 2023), (industrial) wastewater treatment (Rajhi & Bardi, 2023; Sinha, 2022). Efforts to remove pharmaceuticals from water are one of the newest approaches in the field (Banerjee *et al.*, 2022).

Ankit *et al.* (2020) state that the “*application of aquatic macrophytes for the removal of organic contaminants has proved to be an eco-friendly and efficient tool to remediate aquatic ecosystems*”. As an additional benefit, the plants sequester carbon at the same time (Ankit *et al.*, 2020) and the produced biomass can be used for bio-energy production (H. Singh & Pant, 2023). To ensure that the measures do not harm the respective local ecosystem native species should be prioritized (De Souza *et al.*, 2023). The next pages describe three native plant genera chosen for this project.

2.4 MACROPHYTE VEGETATION

Aquatic plants (such as macrophytes) are found all over the world. They thrive in diverse environmental conditions, including swamps, seasonally dry areas and wetlands. Their robustness, resilience and adaptability make them very valuable for various ecological functions, including phytoremediation (Sood *et al.*, 2012).

Aquatic macrophytes are fundamental in nutrient cycling because they absorb nutrients from their environment into new tissues during their growth season. Plants with high annual productivity can thus absorb substantial amounts of nutrients from their environment and can help to reduce nutrient levels from domestic, industrial, and agricultural wastewater (Vymazal, 2008). This includes the nutrients nitrogen and phosphorus which are drivers of eutrophication (Kröger *et al.*, 2007).

Given their high capacity to reduce and assimilate excess nutrients, aquatic plants are often used for treating water pollution in constructed wetlands (Jampeetong *et al.*, 2012). Planting and harvesting aquatic macrophytes is a long-known recommended strategy for improving and maintaining water quality in aquatic ecosystems (Nikolaidis *et al.*, 1996). To ensure the efficiency and sustainability of these efforts, it is pivotal to use autochthonous plants for phytoremediation because native plants are more likely to survive in their local environments without disturbing the existing ecosystems (Muerdter *et al.*, 2018).

The following macrophytes are native to the Algarve region and are therefore relevant to the research project:

The genus *Typha* includes emergent macrophytes commonly found in wetlands. They are highly effective in nutrient uptake, particularly nitrogen and phosphorus and therefore often used in constructed wetlands for wastewater treatment. *Typha latifolia* (see Figure 3) is a resilient species that withstands a wide range of environmental conditions which makes it ideal for phytoremediation projects (Martínez-Martínez *et al.*, 2023; Vymazal, 2013).



Figure 3. *Typha latifolia* (Lindman, 1926)

Phragmites (shown in Figure 4) (also known as common reed) is another genus of emergent macrophytes that grow well in different wetland environments. Its extensive root system helps to have a high capacity for nutrient intake. They are particularly effective in absorbing heavy metals and degrading organic pollutants (Crisman *et al.*, 2014; Eid *et al.*, 2020).



Figure 4. *Phragmites australis* (Thomé, 1885)

The genus *Juncus* includes species that are found in freshwater and saline wetlands. Like the *Phragmites*, *Juncus* can take up heavy metals, nutrients and other contaminants from water and sediments. *Juncus* species (example can be seen in Figure 5) also provide an important habitat for insects (Karstens *et al.*, 2021).



Figure 5. *Juncus inflexus*
(Tackenberg, 1883)

By incorporating these macrophyte genera into floating structures, the balance of nutrients and some pollutants removal can be improved in urban water bodies. Once in place, the plants not only help to remediate eutrophication but also contribute to biodiversity and improved aesthetic value of urban environments. As briefly mentioned in this chapter macrophyte vegetation is often used in constructed wetlands which exist in widely ranging designs using different species. The three featured species chosen for this project will be discussed more in-depth in chapter 3.3.3. Before turning to the project framework and introducing the idea and approach of the study, the next sub-chapters briefly discuss the cycle of the major nutrients, nitrogen and phosphorus, in water bodies.

2.5 NITROGEN AND PHOSPHORUS CYCLE IN LAKES

The nitrogen and phosphorus cycles are indispensable knowledge to improve conditions of (urban) water bodies.

Nitrogen is one of the most important nutrients connected with eutrophication. It undergoes different transformation processes in aquatic nutrient cycling. Nitrogen enters water bodies (e.g. urban lakes) from external sources like rain, (urban) runoff, soil/ sediment deposition or the decomposition of organic material. Microorganisms convert organic nitrogen (e.g. proteins or parts of excrements) into ammonium (NH_4^+) which is the first stage in the conversion of organic nitrogen into inorganic nitrogen forms. Under aerobic conditions (rich in oxygen) ammonium is oxidised by specific bacteria and becomes nitrite (NO_2^-) and then further converted by other bacteria to nitrate (NO_3^-). Aquatic plants, algae and other primary producers can incorporate ammonium, nitrite and nitrate while growing and as a result store nitrogen as plant biomass. In anoxic conditions (low concentrations of dissolved oxygen) denitrifying bacteria convert nitrate (NO_3^-) into gaseous nitrogen (N_2) or nitrous oxide (N_2O) which is released into the atmosphere. This is usually the main way through which nitrogen leaves an aquatic system (Follett, 2001; Jørgensen, 2009).

As said, nitrogen can have two different forms in water bodies, organic and inorganic. While inorganic nitrogen (namely ammonium, nitrate, and nitrite) can be used directly as a source of nutrients by plants and algae, organic nitrogen is usually found in more complex molecules, for example proteins, amino acids or urea. Organic nitrogen must first be converted into inorganic forms by the described microbial degradation before it becomes biologically available for plant uptake (Jampeetong *et al.*, 2012; Rizhinashvili, 2022; Sauer *et al.*, 2001).

Changes in nitrogen availability can also be influenced by phosphorus limitation which sometimes occurs while nitrogen is abundant. Under such circumstances, there is a high level of total nitrogen combined with a low level of phosphorus indicating an imbalance in the nutrient ratio. Nitrogen accumulates in the sediments or the water but cannot be used for algae and plant growth due to a lack of phosphorus (Elser *et al.*, 1990; Rizhinashvili, 2022; Sterner, 2008).

Biological processes like macrophyte activity also influence the distribution of nitrogen and phosphorus compounds in surface waters. Macrophytes can increase oxygen levels in the water through photosynthesis and thereby increase nitrification rates. Their biomass can also contribute to the input of organic matter (which contains organic nitrogen and some phosphorus) through decomposition (Wada *et al.*, 2021). In lakes with a high animal

population, the excrement of these animals can also lead to an accumulation of organic nitrogen, which is only integrated into the inorganic part of the nitrogen cycle after the described microbial conversion (Yin *et al.*, 2018).

Another important nutrient cycle in lakes is the phosphorus cycle which consists of physical, chemical and biological processes that are closely interlinked. The interplay between external input, internal loading, biotic activity and long-term sedimentation influences the phosphorus dynamics and hence the water quality (Correll, 1998; Koue, 2024; Lewis *et al.*, 2011). The most common sources of phosphorus are erosion, agricultural and urban runoff, wastewater or atmospheric deposition (Lewis *et al.*, 2011; Muerdter *et al.*, 2018; Schipanski & Bennett, 2021; Sterner, 2008). Phosphorus is the basis for primary production and taken up by primary producers like phytoplankton, algae and aquatic plants like macrophytes, all of which incorporate it into their biomass (Elser *et al.*, 1990; Schipanski & Bennett, 2021; Vanni, 2002). The uptake process is essential for the growth of these producers and determines the nutrient dynamics of a water body. Phosphorus is often the limiting nutrient under oligotrophic conditions while an excess in eutrophic lakes though can cause algal blooms and oxygen deficiency (Istvánovics, 2008; Schipanski & Bennett, 2021; Vanni, 2002). Phosphorus-containing particles like dead organisms or faeces can settle in sediments and act either as a long-term reservoir or as a direct source of phosphorus depending on the availability of oxygen (Johansson *et al.*, 1998; Schipanski & Bennett, 2021; Søndergaard *et al.*, 2003). Under oxic (oxygen-rich) conditions, phosphorus in the form of phosphates binds to iron(III) oxyhydroxides and is immobilised. In anoxic conditions, iron(III) is reduced to iron(II) which causes the release of phosphate into the water column (Søndergaard *et al.*, 2003).

Remineralisation during which microbial decomposition breaks down organic materials and releases phosphorus as bioavailable phosphate is another important process (White *et al.*, 2012). Aquatic primary consumers and fauna for example zooplankton and fish can transport phosphorus through feeding, excretion and translocation to different locations and depths in water bodies (Andersson *et al.*, 1988; Griffiths, 2006; Schipanski & Bennett, 2021; Vanni, 2002).

Aquatic plants (such as macrophytes) take up phosphorus from the water and sediment, store it in their tissues and can, if not removed, release it again through decomposition (Istvánovics, 2008; Vanni, 2002). Both cycles are important to understand the processes connected with the biodevide and interpret the results presented in chapter 4.1.

The next chapter presents innovative solutions to a variety of problems within the urban water cycle, especially constructed floating wetlands (CFWs).

2.6 INNOVATIVE SOLUTIONS IN THE URBAN WATER CYCLE

As mentioned in the previous chapters human activities have altered the natural water cycle for many years, particularly in urban areas (see chapter 2.1).

This chapter gives a brief overview of innovative solutions in (urban) water management before presenting one particular solution (constructed floating wetlands) which is important for this study.

Among the newest trends in the field of urban water management are digital twins. They are virtual models of physical water systems that contribute to better monitoring and management. These digital copies of physical installations help cities predict and counteract issues like leakages and inefficiencies in the water supply system (Movva, 2024). Smart and connected water meters help to create a real-time overview of the flows within a water supply system and reduce real and apparent water losses (Soares Ascensão *et al.*, 2023).

There are not only digital but also physical solutions which are constantly being improved with two examples being rainwater harvest and greywater recycling systems. Rainwater harvest systems can store rainwater from rooftops and other impervious surfaces mostly for non-potable uses (e.g. irrigation and toilets) and thereby reduce dependency on municipal water supplies and simultaneously help mitigate urban flooding by decreasing the peak runoff (Rodrigues *et al.*, 2023). Greywater recycling involves collecting and treating wastewater from domestic activities like showers and laundry and then reusing them also mostly for non-potable purposes. This practice can reduce residential water use by 10 % to 40 % and is particularly beneficial in arid regions or places with limited freshwater supply like small islands (Diamantis, 2021; Torres *et al.*, 2023).

The challenges innovative solutions in urban water systems aim to address are diverse and always depend on local conditions like local climate, local geographical conditions and existing infrastructure. The solutions chosen for each purpose must therefore be developed/chosen for the specific conditions. Cities with heavy rainfall for example could need rain gardens and bioswales whereas arid regions might need to focus on water conservation and efficient reuse systems (Oral *et al.*, 2020). Green infrastructure can often not only address water management issues but also contribute to urban biodiversity and provide aesthetic and recreational benefits (Liu & Jensen, 2018).

According to Cong *et al.* (2023) cities and municipalities that integrate innovative solutions should make sure their implementation and operation contribute minimally to CO₂ emissions. This means that sustainable urban water management practices should prioritize low-carbon

technologies and materials. Using local and natural materials for constructing green infrastructure for example reduces their carbon footprint.

A particularly innovative green solution is constructed floating wetlands (CFWs), which can be deployed in various (urban) water bodies with minimal structural changes and a positive ecological impact. CFWs consist of buoyant platforms in which plants are placed. They use the natural processes of plants and associated microorganisms to remove pollutants from the water through phytoremediation (see chapter 2.3). The roots of the plants extend into the water, where they absorb nutrients and contaminants, helping to improve water quality (Ayres *et al.*, 2022; Pavlineri *et al.*, 2017). Figure 6 shows a schematic representation of CFWs.

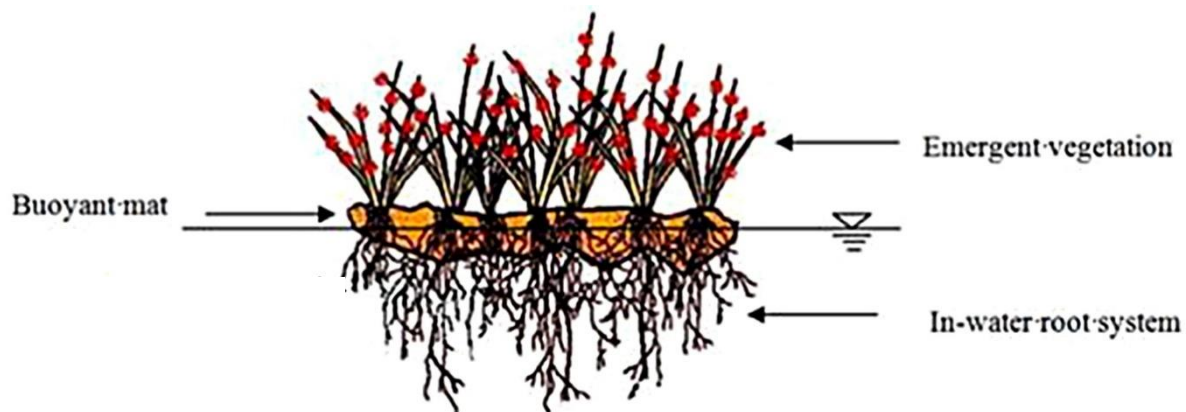


Figure 6. Scheme of constructed floating wetland (adapted from Pavlineri *et al.*, 2017)

There are numerous further advantages of CFWs:

- Mobility and scalability: CFWs can easily be installed in and adapted to different locations as needed which makes them flexible according to their use cases. They can for example adapt to changing water levels easily and their size is adaptable.
- Minimal infrastructure: CFWs require little to no modification of existing water bodies, making them cost-effective and easy to implement. They also have low maintenance costs, since almost no special equipment or personnel is required. CFWs have low to inexistent energy costs after being deployed.
- Ecosystem services: Besides improving the water quality, floating wetlands contribute to improved biodiversity. Different animals can use them as a habitat.
- Aesthetic value: CFWs can also improve the visual appearance of urban water bodies and thereby contribute to the overall quality of urban life (Calheiros *et al.*, 2020; Karstens *et al.*, 2021; Machado *et al.*, 2020; Mfarrej *et al.*, 2023).

Innovative solutions like CFWs contribute to more sustainable and resilient urban water cycles. By mimicking natural processes and customizing the solution to regional needs while minimizing CO₂ emissions, cities can aim to effectively manage water resources which is why this technique was chosen for this study. The construction process of the new biodevice will be described in the following chapter after presenting the area under study and the methodologies used to assess water quality and cork characteristics.

3

MATERIALS AND METHODS

This chapter will introduce not only the physical and morphological characteristics of the study site but also the methods used for the water quality characterisation, cork characterisation as well as the biodevice development and its construction process.

3.1 STUDY SITE

3.1.1 THE AREA UNDER STUDY

The lake studied in this thesis is in the city of Almancil (see Figure 7) in the Algarve region of Portugal. It is located in the city's central park (Jardim das Comunidades),

The Portuguese Institute for Sea and Atmosphere (IPMA) classifies the climate in the area under study as Csa following the Köppen-Geiger climate classification, also known as a hot-summer Mediterranean climate. This classification is characterized by hot, dry summers and mild, wet winters (Andrade & Contente, 2020).



Figure 7. Satellite image localisation of Almancil on the southern Iberian peninsula (*ALMANCIL Geography Population Map Cities Coordinates Location - Tageo.Com, n.d.*)

The closest IPMA climatological long-term data set is from the meteorological station at Faro Airport (Instituto Português do Mar e da Atmosfera [IPMA], 2023) which is at a distance of 9.28 km from the area of study as determined using Google Earth Pro. Due to this distance, the exact climatic values for Almancil may vary slightly from those recorded at Faro Airport. The climate normal (1981-2010)¹ for Faro indicates an annual precipitation of 511.6 mm and a mean daily air temperature of 17.9°C (IPMA, 2023). As shown in Figure 8, there are almost no precipitation events during the summer months but high average temperatures (see Figure 9).

¹ The most recent climate normal data sheet provided by IPMA is the one used for this thesis.

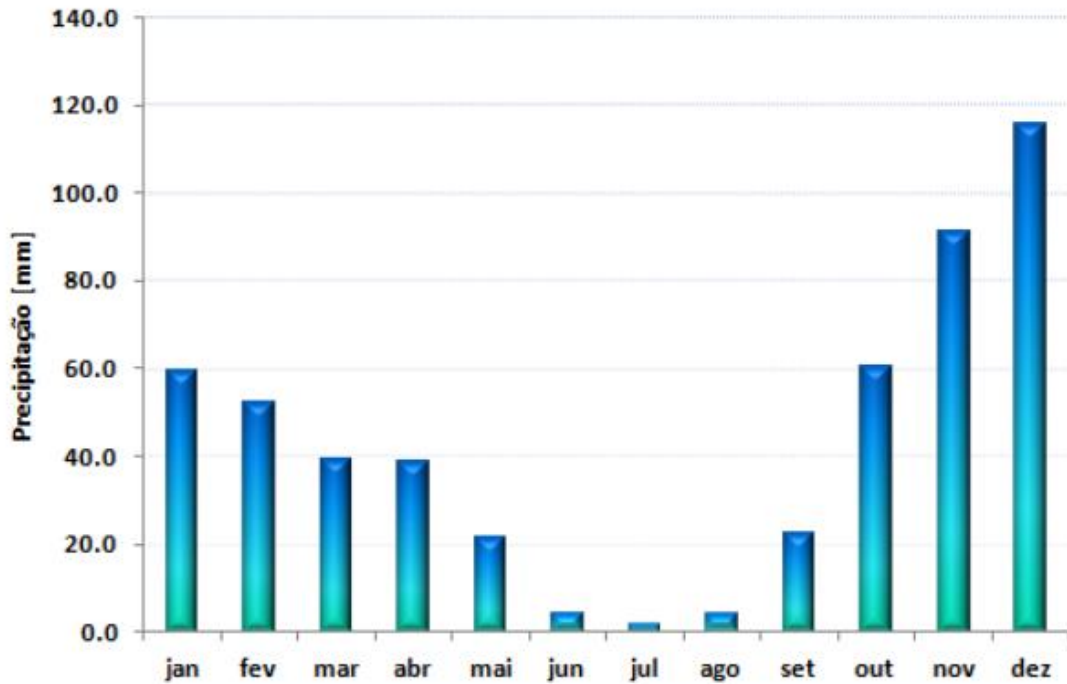


Figure 8. Monthly precipitation means (climate normal 1981-2010) at IPMA station 554 (Faro Airport) (Instituto Português do Mar e da Atmosfera - IPMA, 2023)

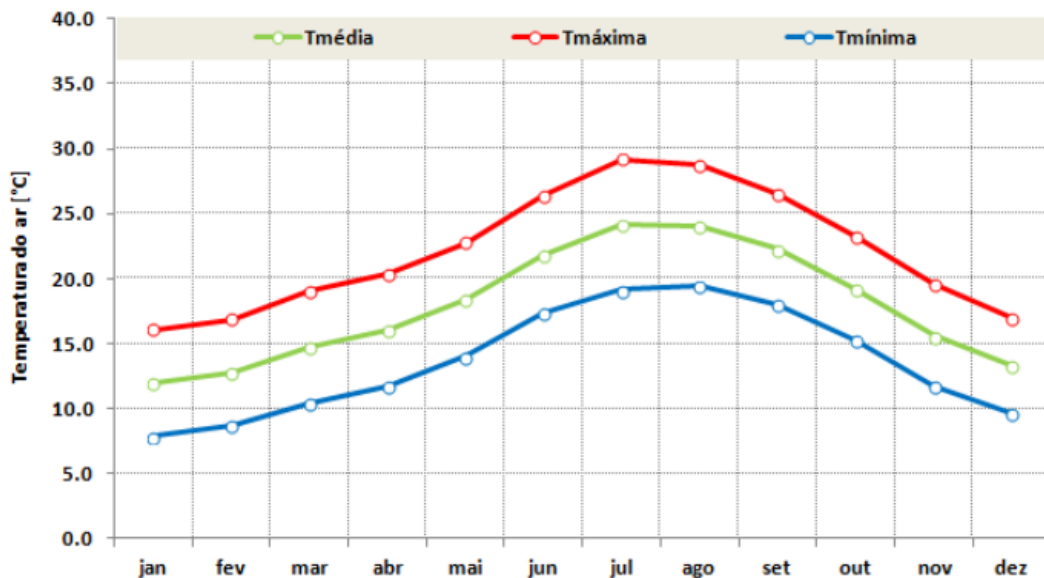


Figure 9. Maximum, average and minimum temperatures (climate normal 1981-2010) at IPMA station 554 (Faro Airport) (Instituto Português do Mar e da Atmosfera - IPMA, 2023)

IPMA (2023) shows that winter precipitation is often concentrated in heavy rainfalls rather than continuous light or moderate rain. Due to global warming, it can be assumed that strong precipitation events will become heavier while the total precipitation decreases further (Zittis *et al.*, 2021).

Evaporation rates increase during the dry and warm summer months, which can concentrate nutrients and pollutants in lakes and thereby potentially increase eutrophication (Wang *et al.*, 2023). The wet winters with their heavy rainfall events could lead to runoff that introduces additional nutrients and contaminants into the lake (Yang & Lusk, 2018).

The lake is part of a park in Almancil (Jardim das Comunidades) which can be described as a focal point for the community's recreational activities. The public park was constructed in 2003 (Pimenta *et al.*, 2021) and is surrounded by a high school, a kindergarten, a social and cultural association, and residential apartment blocks of which some have cafes in their basements. The park itself features installations for recreational purposes such as a playground, benches, and a small building right next to the lake, which contains public toilets and a room to host community activities like yoga and seniors' dance classes. Figure 10 provides a comprehensive overview of these points of interest (POIs).

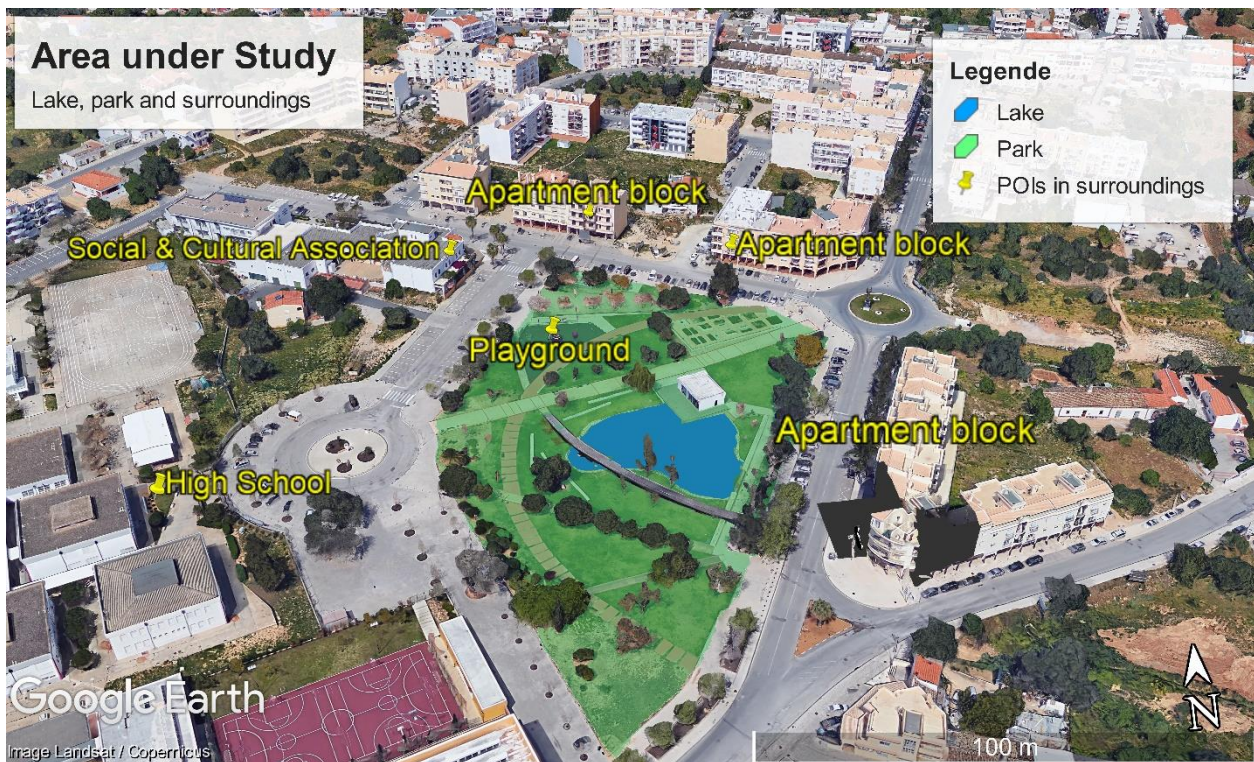


Figure 10. Adapted satellite image of the area under study (GoogleEarth Pro (Desktop), 2024)

The park covers a total area of 12,180 m², including the lake. The lake is an artificial urban water body supplied with drinking water (Pimenta *et al.*, 2021). The next chapters provide more details on the morphology of the lake and its functioning.

3.1.2 LAKE MORPHOLOGY

Moses *et al.* (2011) state that surface area, depth, and shoreline length are among the important parameters influencing water quality and these parameters are known for the lake in Almancil. As mentioned, the lake in Jardim das Comunidades, Almancil, is an entirely artificial water body. The lake spans an area of around 1200 m² and has a maximum depth of 1.30 m (Moreira Da Silva, 2022). It exhibits an irregular outline, as shown in Figure 11.



Figure 11. The lake of Jardim das Comunidades – Almancil, under study view from SSW to NNE (Picture by author, 27.01.2022).

Its shoreline includes a visitor platform and an overflow area that feeds a turbidity system (to be described in the next subchapter). The biggest part of the shoreline is constructed with rows of undefined stones forming multiple steps. The approximate shoreline length, as determined by the polygon drawn in Google Earth Pro, is 148 meters (see Appendix A for the screenshot of polygon properties).

There are no plants along most of the shoreline, presumably to not obstruct the view on to the lake. On the east side of the lake, there is the overflow in which some aquatic plants (not further specified or monitored) are integrated.

These morphological characteristics are intended to describe the study environment of this thesis rather than being its core focus. They give the necessary background information to understand the functioning of the lake which will be assessed in the next paragraphs.

3.1.3 FUNCTIONING OF THE LAKE

Since its construction the lake in Jardim das Comunidades in Almancil has faced recurring issues with eutrophication, green microalgae blooms and the risk of cyanobacteria. Given the lake's central location in the park, there is the constant possibility of visitors, pets and children coming into contact with the water. The lake has never been used for recreational activities (e.g. swimming) and there are no plans to change this.

The lake is supplied with potable water treated for human consumption. At the end of 2019, an intervention was carried out to clean the accumulated anoxic sediments at the bottom of the lake and to improve its water circulation by changing the water supply system. In 2021 the hydrodynamics of the lake were optimized using a circulation system which operates with pumps powered by public grid energy. The system was repaired and improved to ensure there were no stagnant zones with stratification that could potentially become anoxic during night periods. All necessary efforts were made to maintain a circulation flow of 50 m³/h through various water inlets (I1 to I6 in Figure 12) (Pimenta, 2021; Santos, 2021).

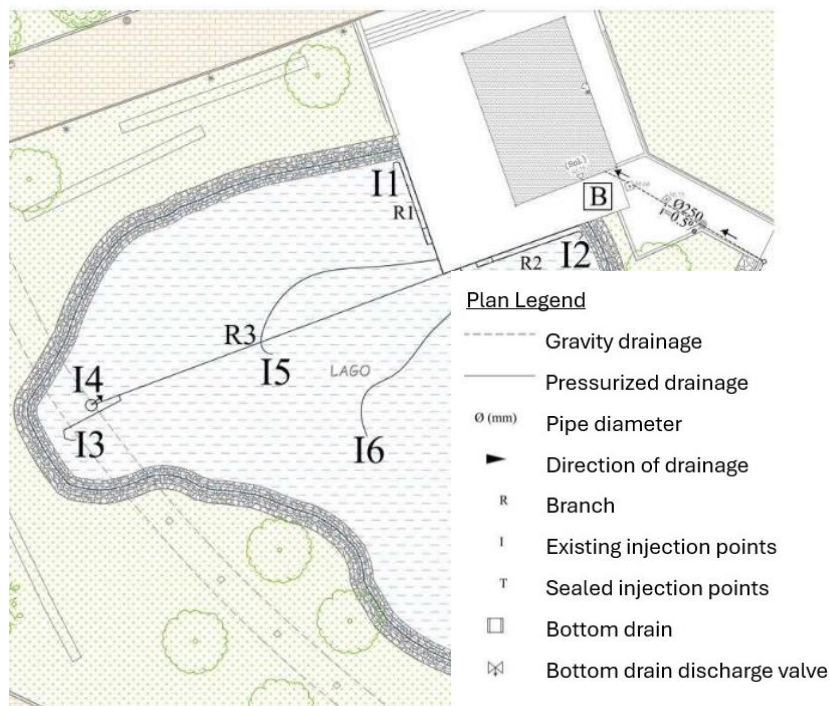


Figure 12. Plan of turbidity system installed in the lake under study (Santos, 2021)

In June 2021 there a volunteer action took place to remove exotic turtles and other invasive species from the lake that were destabilizing its ecosystem (Sul Informação, 2021). For further action against eutrophication, a commercial product for nutrient phytoremediation was installed in December 2020 but did not perform well (Pimenta, 2021).

The underperformance of the commercial product led to the idea to create an “in-house biodevice”. The conceptualization and genesis of it is the subject of the next subchapter.

3.1.4 CONCEPTUALIZATION AND GENESIS OF THE BIODEVICE

Due to the high concentrations of nutrients (mainly N and P), the lake in Almancil has experienced some eutrophication problems, despite the installation of a mechanical solution involving a pump system designed to create water flow. This system is very helpful, however insufficient for addressing the high concentrations of N and P in the lake. This context laid the foundation for exploring more sustainable and innovative approaches, based on natural solutions, to balance the water quality in this urban lake.

The idea for a new biodevice emerged from the observation of a commercial product tested before. That commercial product was used and degraded after a few weeks. The necessity of a more durable and sustainable NbS led to the development of a prototype using locally sourced materials—specifically, native cork from local oak trees and native macrophyte species. The new device aims to use the natural abilities of phytoremediation to tackle eutrophication effectively.

In developing the prototypes of this biodevice, the project involved a close collaboration between the Institute of Engineering - University of Algarve (ISE-UA) and Loulé Municipality. These stakeholders provided the necessary support and resources for the development and implementation of the biodevice which ensured that the solution was both scientifically sound and practically feasible. The construction of the biodevice comprised the assembly of CFWs with cork pieces connected in slightly different ways and serving as the buoyant platforms holding the selected macrophytes. These platforms were then anchored in the lake, allowing plant roots to extend into the water column and begin the remediation process.

Evaluating the effectiveness of the biodevice required periodic monitoring of water quality parameters such as nutrient levels (nitrogen and phosphorus), chlorophyll *a*, dissolved oxygen,

and others. Data collected from these evaluations helped to assess the performance of the biodevice and will guide any necessary adjustments to improve its efficiency in the future.

Additionally to the main installation in Almancil, a mini-version of the biodevice was installed in a small pond at the interactive museum Centro Ciência Viva do Algarve (Faro) to contribute to the educational aspect of sustainability. This smaller installation serves as a demonstration model, educating visitors about the principles and benefits of phytoremediation and sustainable water management. The informational flyer provided in chapter 4.4 and this thesis will enable tour guides to explain the device's function to their visitors.

The biodevice combining macrophytes and local cork could potentially represent a promising solution for the remediation of nutrients and pollutants in urban lakes. By integrating phytoremediation with the local material cork this approach could offer a sustainable method for improving urban water quality.

The construction, implementation, and evaluation of this biodevice are detailed in the subsequent sections of this thesis and evaluate its potential to address eutrophication and contribute to the ecological health of urban water bodies.

The next chapter describes the methodology around the water quality characterization used to measure the impact of the developed prototypes on the functioning of the lake.

3.2 WATER QUALITY CHARACTERISATION

The water quality analysis is a key part of this dissertation since it evaluates the biodevices effectiveness. It was essential to have data for an extended period to gain a deeper understanding of the processes affecting water quality in the lake. Measurements from previous projects were available for November 2019 and February 2020. Two additional data sets (2022 and 2023) were generated as part of this thesis. *In-situ* measurements were performed, and samples were taken on 17th June 2022 and 15th June 2023 using the same methods on both occasions to ensure comparable results. Sampling was conducted at three specific locations in the lake which can be considered representative of the overall water quality: near the building, near the bridge, and near the overflow (see Figure 13). All tests and samples were taken at these points to maintain consistency and reliability in the data collected.



Figure 13. Lake of Jardim das Comunidades and locations of water sampling (GoogleEarth Pro (Desktop), n.d.).

To assess the water quality, *in-situ* measurements (see Figure 14) and laboratory analyses were conducted with water samples collected during fieldwork.



Figure 14. *In-situ* measurements on 17.06.2022 (Picture taken by Prof. Doutora Manuela Moreira da Silva)

All the *in-situ* and laboratory analyses at ISE-UAIlg were performed according to Baird *et al.* (2017).

The *in-situ* measurements were performed in triplicate for each parameter with the following devices:

- a Secchi disk with a 15m cord for measuring water transparency (producer: The Science Source; Model No. #15020)
- a portable Multimeter Hach HQ 30d², as part of the HQd Field Case Cat. No 5825800, with the following probes:
 - IntelliCAL PHC101³ rugged probe to measure the pH with a range of 2 to 14 pH and an accuracy of ± 0.02 pH. Temperature was measured with the same probe and an accuracy of ± 0.3 °C within the operating temperature of 0 to 50 °C and a resolution of 0.1°C.
 - IntelliCAL LDO101⁴ rugged probe to measure dissolved oxygen with an accuracy of ± 0.1 mg/L from 0 to 8 mg/L/ ± 0.2 mg/L for greater than 8 mg/L; 0.8% and a range of 0.05 - 20.0 mg/L; 1 - 200% saturation. The resolution is 0.1 for concentration and saturation.

Temperature, pH and dissolved oxygen were measured *in-situ* using the multimeter probes. Temperature was recorded in degrees Celsius (°C), while pH was determined on the Sorensen scale. The dissolved oxygen results were expressed in milligrams per litre (mg.L⁻¹) and percentage (%). Transparency was also measured *in-situ* using Secchi disk visibility, in centimetres (cm)⁵.

² <https://de.hach.com/hq30d-digitales-multimeter-kit-ldo-sensor-outdoor-5-m/product-details?id=26370217280> (last visit on 29.09.2024)

³ Data sheet can be requested from the author.

⁴ <https://www.hach.com/p-intellical-ldo-probes/LDO10105> (last visit on 07.01.2025)

⁵ None of the researchers involved in the study questioned the collection of transparency data using the Secchi disk method during the data collection phase. During the evaluation of the data, an error became apparent, which is explained in more detail in chapter 4.1.1. Secchi disk transparency is not suitable for shallow lakes with ground visibility and will therefore not be described further in this chapter.

The laboratory equipment used for the nutrients and chlorophyll *a* measurements was a UV-VIS Spectrophotometer Thermo Scientific model Evolution 300 UV-VIS⁶ with the uncertainties for the tested parameters shown in Table 2. Uncertainties for the laboratory .

Table 2. Uncertainties for the laboratory water tests

Parameter	Unit	Expanded uncertainty
Ammonia	mg/L	8.2 %
Phosphates	mg/L	10.5 %
Chlorophyll <i>a</i>	mg/m ³	20 %
Total phosphorus	mg/L	6.9 %
Total nitrogen	mg/L	20%
Nitrates	mg/L	10.4 %
Nitrites	mg/L	16.5 %

For the laboratory analyses, samples were taken at the designated spots and contained in 1 litre plastic laboratory bottles which were immediately cooled after collection to ensure the integrity of the samples. The samples were taken at a depth around 20 cm. The laboratorial analyses were conducted in the Laboratory of Sanitary Engineering of the ISE-UAAlg.

Orthophosphates (PO_4^{2-}), total phosphorus (TP), ammonia (NH_4^+), nitrates (NO_3^-), nitrites (NO_2^-), and total nitrogen (TN) were quantified in milligrams per litre ($\text{mg}\cdot\text{L}^{-1}$) using molecular absorption spectrometry. Chlorophyll *a* was also analysed by molecular absorption spectrometry but with concentrations recorded in milligrams per cubic meter ($\text{mg}\cdot\text{m}^{-3}$).

All the procedures were supervised by an experienced technician from the Laboratory of Sanitary Engineering at UAAlg to ensure the accuracy and reliability of the data collected. The

⁶ <http://tools.thermofisher.com/content/sfs/brochures/D10956~.pdf> (last visit on 07.01.2025)

calibration of the multimeter probe was undertaken by the same technician before coming to the field. The processing of the samples in the lab was covered by the project with the CM Loulé.

Following the study design of Hu *et al.* (2014), which focuses on the trophic state of shallow lakes, an adapted Carlson's trophic state index (TSI) was calculated using three limnological parameters:

$$\text{TSI(Chl-}a) = 10 \times (2.500 + 1.086 \times \ln\text{Chl-}a)$$

$$\text{TSI(TP)} = 10 \times (9.436 + 1.624 \times \ln\text{TP})$$

$$\text{TSI(TN)} = 10 \times (5.453 + 1.694 \times \ln\text{TN})$$

Where Chl-*a*- is the Chlorophyll *a* concentration expressed in mg/m³; TP and TN the Total phosphorus and Total nitrogen concentrations, expressed in mg/L.

After calculating the Trophic State Index (TSI), the ecological classification of the lake was determined according to Hu *et al.* (2014), as shown in Table 3.

Table 3. Interpretation of Trophic State Index (Jin *et al.*,1995 in Hu *et al.*,2014)

Trophic State Index (TSI)	Ecological Classification
0 < TSI ≤ 30	Oligotrophic
30 < TSI ≤ 40	Oligo-mesotrophic
40 < TSI ≤ 50	Mesotrophic
50 < TSI ≤ 60	Slightly eutrophic
60 < TSI ≤ 70	Moderately eutrophic
70 < TSI ≤ 100	Hypereutrophic

The described procedure was a first approach to classify the ecological status of this lake and was an adapted form of Hu *et al.* (2014) which is based on 3 replicates of 3 water samples, to characterize this lake.

In addition to the measurements, some field visits were conducted to observe the structural integrity of the prototypes and some visual inspections of the lake (colour of water, presence of exotic fauna, etc). The study design was conditioned by the urgent need for the prototypes installation to avoid degradation of the water quality in the lake, namely related to seasonal

factors (temperature, insolation, etc.) and to potential fertilizer (including N and P) and pesticide runoff from the lawn surrounding the lake.

To minimize the impact of seasonal variations, the two samples collected during the study were collected around the same date of each year, but it is impossible to completely exclude the influence of weather conditions throughout the year that lay in between.

It was not possible to introduce the different prototypes of the biodevice at the same time because there were restrictions on labour and transport vehicles from the yard to the lake.

The current assessment is enough to have a first assessment of the biodevice's feasibility. However, it is necessary to keep assessing the ecological state of the lake with a larger and more intensive research design to confirm its efficiency. This could include more frequent water sampling of nutrients and Chl *a* testing, and integrating automatic monitoring systems/sensors, at least for temperature, ammonia, and dissolved oxygen.

Despite the described constraints, the chosen methodology provides a reasonable indication of the biodevice's impact on water quality. However, acknowledging these limitations is essential for interpreting the results of this study and planning potential future studies.

The next chapters will describe the process of the biodevice development with a focus on its design and materials.

3.3 BIODEVICE DEVELOPMENT

The idea to use a constructed floating wetland (CFW) made from cork in the lake in Almancil emerged after the use of a commercial product that used cork agglomerates, and which did not work in this lake. With a lot of cork production in the Algarve region, the municipality thought about using this resource and developing a new biodevice that was nature-based and without commercial interests.

The following chapters discuss the choice of materials, the assessment of their properties and outline the construction process.

3.3.1 CHOSEN MATERIALS AND THEIR PURPOSE

Mainly three different kinds of material were used for the construction of the biodevice: pieces of natural cork, macrophyte plants and rope from the nautical sector.

The choice of materials was based on the general design idea and on the principle of using as many local and natural components as possible. The Algarve region in Portugal is known for

its cork production, so pieces of local natural cork were chosen as buoyant material. Several advantages of this material are being discussed in the following before providing details about the other two components, rope and plants.

One of the key goals of constructed floating wetlands is that the body of the island has a good buoyancy in order to hold the plants (except roots) above water level (Ayres *et al.*, 2022). Cork has good buoyancy which makes it an ideal material for constructing floating platforms (Pereira, 2007a).

Another reason for choosing cork is that the support of local sustainable cork production is important because cork oak forests contribute to ecological balance within their growth regions. This kind of forest supports a wide array of ecosystems and helps to prevent desertification (Pereira, 2015). Portugal has over 700,000 ha of cork oak forests and is one of the biggest producers worldwide (Palma *et al.*, 2014). The cork oak tree also has a good capacity for carbon sequestration. According to Palma *et al.* (2014) an individual oak tree can store between 0.4 and 2.2 Mg of carbon over 80 years of growth, which corresponds to 35–136 Mg C ha⁻¹ at the stated tree density of the study. According to APCOR – Associação Portuguesa da Cortiça (2019), cork can be compressed to about half its width without losing any flexibility, and it recovers its shape and volume as soon as it is no longer pressed. It is the only solid natural material which, when compressed on one side, does not increase in volume on the other. Cork is already used for various purposes, for example in the beverage and building industries, and is consistently regarded as a sustainable material (Knapic *et al.*, 2016).

Cork offers a sustainable alternative to some existing solutions for providing buoyancy in constructed floating wetlands, which often use plastic materials like PVC pipes (see for example Trang *et al.*, 2024). For a detailed description of the specific characteristics of the cork chosen for this study see chapter 4.2. as this chapter provides insights into the properties of the cork used in the floating structures created in this study.

To tie the cork pieces together, it was necessary to use rope which was originally supposed to be made from natural materials. Given the concerns of the municipality of Loulé about durability, a nautical rope was selected instead. The requirement for the rope to withstand prolonged exposure to sun and water led to a product from the yachting industry, specifically a brown braided polyester rope from the company Regatta Yacht Ropes with a diameter of

3mm⁷. This diameter was selected to ensure that the rope would not tear under tension nor be so small that it might cut through the cork pieces when subjected to tension and movement. For the anchoring, a thicker yachting rope with a diameter of 10mm was used.

As discussed in chapter 2.4 and 3.3.3, the selection and use of plants were integral to the design and functionality of the floating platforms. To ensure compatibility with the local ecosystem and to avoid introducing potentially invasive species, only autochthonous macrophyte species were used. Pre-grown plants were ordered from a plant supplier to ensure they were mature enough to survive and thrive in the hydroponic conditions of the floating platforms. The plants arrived in square plastic plant pots, with varying amounts of soil and root distribution.

The exact reasoning for the choice of the plants is described in chapter 3.3.3 while the next chapter describes the methodologies used to characterise the cork.

3.3.2 CORK CHARACTERISATION METHODS

To examine the properties of the cork used in the biodevice a variety of tests were conducted to determine its colour, texture, and density. This chapter details the methods used and provides an overview of the experimental procedures.

For this part of the study, thirty 5 cm x 5 cm cork cubes were prepared and analysed. These cubes were sourced from ten different boards with three cubes taken from each board using a jigsaw. Appendix C provides photographs of these ten sample boards and the locations the sample cubes were taken from.

The following paragraphs provide a detailed overview of the methodologies used to determine the colour, texture, and density of the cork.

⁷ See page 64, Reference 00141 in <https://www.cabosregatta.com/wp-content/uploads/2023/05/CATALOGUE-REGATTA-2022-ENG.pdf> (last visit on 29.09.2024)

a- Colour:

Colour measurements were conducted in triplicate on three surfaces of the 30 samples (n=30): bark, cut-side (surface exposed during sample preparation), and inside (opposite the bark). Measurements used the CIE system [L^* (lightness, 0 for black to 100 for white), a^* (red-green) and b^* (yellow-blue)] with a tristimulus colorimeter (PCE Ibérica, model CSM-10, Spain⁸) at room temperature based on the method reported by Romero *et al.* (2022) with some modifications. The colorimeter (d/8° geometry, illuminant D65, 10° observer) was calibrated against a standard ceramic white tile ($X=85.06$, $Y=89.81$, $Z=93.33$) and a standard ceramic black tile ($X=0.08$, $Y=0.07$, $Z=0.09$). The repeatability of spectral reflection measurements demonstrates a standard deviation of approximately 0.1% (400–700 nm: within ~0.2%), with colorimetric values exhibiting a standard deviation within ΔE^*_{ab} 0.04, and inter-equipment errors remaining within ΔE^*_{ab} 0.02.

b- Texture:

The texture of each sample was analyzed using an Instron Universal Testing Machine (Instron, 1011 series, USA⁹) equipped with a 5 kN load cell. The accuracy of the force range is within $\pm 1\%$ when unloaded and $\pm 2\%$ at 5000 N. Based on the method reported by Park *et al.* (2023) with some modifications, a penetration test was performed in the center of each sample with a target value of 3 cm. A stainless-steel probe (T372-31) with a flat end, 4.8 mm diameter, and 15 cm long was used to penetrate the sample and the test speed was set at 50 mm/min. Peak force was used to quantify the hardness (N) of the samples. 30 samples were measured at room temperature. This test was undertaken at last since it left the sample cubes perforated with a hole.

c- Mass measurement: Samples (n=30) were dried in a Binder model FED 240 oven at 60°C for over 12 hours, then stored in desiccators. The mass of each sample was measured in grams using a Mettler Toledo model XS 204 laboratory scale.

⁸ https://www.pce-instruments.com/english/api/getartfile?_fnr=1055314&_dsp=inline (last visit on 07.01.2025)

⁹ <https://frankbacon.com/product/1k-5-kn-instron-1011> (last visit on 07.01.2025)

d- Volume measurement:

The size and volume of the cork cubes were assessed using two distinct methods: a calliper gauge and water displacement. Given the natural variability of cork, water displacement was favoured for its accuracy in capturing the true volume. The calliper gauge was not able to fully measure all the cracks and uneven surfaces of the sample cubes.

- By dimensions: The height, width, and length of each sample cube were measured using an analogue calliper gauge (standard hardware store quality).
- By water displacement: A screw-top jar filled with fishing lead and water was used as ballast to submerge the cork samples in a 2000 ml graduated cylinder (SkyLab) filled with 500 ml of water. Displaced water was transferred to a 50 ml graduated cylinder using a pipette for precise measurements of how much water was displaced. This process was undertaken to determine the jar's volume (270 ml) and subsequently the net volume of each cube after deducting the jar's volume (see Appendix D for description of test set up).

e- Density:

Density (g/cm³) was calculated as the ratio of the sample's weight to its volume. Both the dimension-based and water displacement-based volumes were used, with the latter preferred due to the irregularity of the sample surfaces (e.g., ripples).

The buoyancy/load capacity of water-soaked cork is important to know how many plants the biodevice can support but was not tested with laboratory methods. There was however a simple *in-situ* test using parts of a dumbbell and a 25cm x 133cm (= 0.3325 m²) big piece of cork with a thickness of 6cm that had been in the water for 397 days. See Appendix F for pictures of the test setup. These values are not reliable and can only be seen as a rough estimate. Detailed testing of the soaked cork would have exceeded the scope of the thesis. Further testing in this direction would be interesting for future research to determine how many plants each board can support after a long time in the water. The choice of the plants used for this project is described in the next chapter.

3.3.3 MACROPHYTE SPECIES CHOSEN AND THEIR RATIONALE

While designing this NbS the choice of the plant species was crucial because it directly influences the effectiveness of this biodevice. Due to the underlying design of CFWs only plants could be considered that survive under hydroponic conditions. The next paragraphs describe the chosen species, and why they have been chosen for inclusion in the prototype.

Chapter 2.2 already gave an introduction into some of the principles that should be followed when designing new solutions for NbS in the water sector. Ayres *et al.* (2022) analysed a wide range of studies that dealt with constructed floating wetlands and highlighted the following recommendations for plant selection:

- “ (i) Use native, non-invasive species.
- (ii) Use perennial species.
- (iii) Use terrestrial species (rather than submerged or free-floating macrophytes).
- (iv) Use wetland plants or species that thrive in a hydroponic system.
- (v) Use plants with aerenchyma for greater oxygen diffusion to roots and rhizomes”.

A study that tested the commercial cork island in Port Marina – Porto follows most of the suggestions above and adds “possibility to form a polyculture” to the list (Calheiros *et al.*, 2020). Since the biodevice developed in this study is tested in a city park, the criteria of good aesthetics and being non-poisonous were added.

For our prototype, the following three types of plants fit the criteria described and were therefore selected to be planted in the floating device made from cork:

1. *Juncus inflexus* (hard rush)
2. *Typha latifolia* (cattail)
3. *Phragmites australis* (common reed)

These species were selected as being indigenous, growing naturally in the local environment. Secondly, these macrophytes thrive under hydroponic conditions and have well-developed and efficient root systems for nutrient removal and general improvement of water quality.

The following paragraphs give more details about each species and why there were chosen for the prototype in Almancil.

Ayres *et al.* (2022) mention that *Juncus*, *Typha* and *Phragmites* are among the plants most used for CFWs. They cite a review undertaken by Colares *et al.* (2020) that states plant tissue nitrogen uptakes was in the range of 0.51 to 51.8 g/m², phosphorus uptake rates ranged from

0.062 to 28.3 g/m² and that biomass dry weight ranged from 7.8 to 3600 g/m² (Ayres *et al.*, 2022).

Juncus species (for example *Juncus inflexus*) have repeatedly been used in constructed floating wetlands and their ability to remove pollutants from water bodies is proven (Lucke *et al.*, 2019).. In the previously mentioned study from Porto, *Juncus* was also used and demonstrated its adaptability to rough conditions (Calheiros *et al.*, 2020).

In a study on the potential of different *Juncus* species, *Juncus inflexus* is emphasised as a particularly robust plant for phytoremediation applications. *Juncus spp.* are particularly suitable for the removal of nutrients like nitrogen and phosphorus in various wetland systems. *Juncus spp.* plants contribute to the promotion of microbial activity by releasing oxygen into the rhizosphere, which supports nitrification and denitrification. Studies show that up to 83.5 % nitrogen and 45.5 % phosphorus were removed in floating treatment systems, with *J. inflexus* being a particularly robust and efficient species in such systems. These properties make it a favoured choice for the treatment of wastewater and eutrophic waters (Syranidou *et al.*, 2017).

In a systematic review by Justino *et al.* (2023) *Juncus inflexus* is mentioned as part of CWs. *Juncus inflexus* showed effective removal of organic matter and nutrients including nitrogen and phosphorus. The high adaptability of *Juncus inflexus* to different environmental conditions contributes to its efficiency in CWs. The results demonstrate that *Juncus inflexus* plays an important role in improving water quality and helps to promote sustainable solutions for reducing nutrient pollution. *Juncus* is endemic to the south of Portugal, thus providing a compatible function in the local ecosystem upon its introduction (M. Rodrigues *et al.*, 2014).

A laboratory study investigated the efficiency of *Typha latifolia* and *Juncus inflexus* in removing nitrate from surface water. *Typha latifolia* showed the best performance with a removal efficiency of 95 %, followed by *Juncus inflexus* with 85 % after ten days. Both plants increased the pH value of the water. The results show that the plants can be used to reduce nitrate pollution and thus contribute to improving water quality (Ghamary & Mohajeri, 2021). This emphasises the potential of *Typha latifolia* and *Juncus inflexus* as sustainable options for reducing water pollution and preventing eutrophication.

Typha is one of the major genera in phytoremediation, given its wide distribution across natural aquatic and semi-aquatic ecosystems globally and its ability to survive even in polluted environments. Species of *Typha* are widely used in phytoremediation due to their fast growth, high biomass production, and ability to accumulate heavy metals in their roots. *Typha* host rhizobacteria that have synergistic effects on plant growth (Martínez-Martínez *et al.*, 2023).

A Polish study looks at the potential of *Typha latifolia* to reduce eutrophication in ponds. According to the study, the plant has a high ability to absorb excess nutrients namely nitrogen (N), phosphorus (P), potassium, magnesium and calcium from sediments and thus improve water quality. The authors state that it makes a decisive contribution to reducing eutrophication in ponds. The ability to take up nutrients depends on the physico-chemical properties of the bottom sediments, especially the pH and organic matter content, which emphasises its flexibility in different environments. The study summarises that these properties make the plant a promising, environmentally friendly solution for reducing water pollution and supporting aquatic ecosystems (Parzych & Sobisz, 2023).

A study by Gebeyehu *et al.* (2018) on *Typha latifolia* for the treatment of brewery wastewater shows that the plant grows well in hydroponic systems and has a high nutrient removal capacity. Relatively high efficiency values were obtained in the removal of nitrogen and phosphorus compounds, e.g. between 54-80% for total nitrogen and 51-70% for phosphate. The system produced a biomass of 0.61-0.86 kg dry matter per square metre. The nutrients retained were up to 21.17 g N and 2.87 g P per kg dry matter. These results emphasise the potential of *T. latifolia* in hydroponic systems.

Within constructed wetlands, *Typha latifolia* has been widely used. The species is indigenous and very well distributed in Portugal. Further, the performance of *Typha* for long-term treatment applications has been reported within constructed wetlands for tannery wastewater, evidencing its strength and efficiency in removing nutrients and therefore preventing eutrophication (Calheiros *et al.*, 2008).

The third chosen species, *Phragmites australis* is also widely recognized for their phytoremediation capability (Lei *et al.*, 2023). The study performed on tannery wastewater from northern Portugal has demonstrated high removal rates of organic contaminants by *Phragmites australis*. The plant reached high biochemical oxygen demand removal and large reductions in nitrogen levels (Calheiros *et al.*, 2009).

A study by Li *et al.* (2014) shows that *Phragmites australis* plays a key role in the uptake of nitrogen (N) and phosphorus (P) in wetlands and thus contributes to the reduction of eutrophication. The average contents of the whole plant are 14.1 ± 5.3 mg N/g and 0.95 ± 0.54 mg P/g. The highest N and P concentrations were measured in leaves (31.4 ± 5.2 mg N/g) and flowers (2.05 ± 0.33 mg P/g), while stems had the lowest values. The N and P contents in roots and rhizomes correlate positively with the nutrient concentrations in water and sediment, which emphasises the buffering function of these organs. According to the authors, these

mechanisms make *P. australis* an efficient plant for nutrient removal and stabilisation of wetland ecosystems.

A study from China on shallow eutrophic lakes shows that *Phragmites australis* (reed) has a high capacity for nutrient uptake. The maximum nitrogen and phosphorus stores in aboveground plant parts reached values of 74.5 g/m² TN and 7.3 g/m² TP, while values of 36.1 g/m² TN and 6.7 g/m² TP were observed in belowground parts. The highest nutrient stores occurred in August and September, indicating a seasonal peak in nutrient accumulation. The results illustrate that *P. australis* is particularly efficient at nutrient uptake and storage in nutrient-rich zones, indicating its adaptation to high nutrient loads. This makes it a promising plant for the reduction of eutrophication and the improvement of water quality in polluted waters (Y. Zhao *et al.*, 2013). *Phragmites australis* was also chosen in the project in Porto during which it proved its effectiveness in hydroponic conditions (Calheiros *et al.*, 2020).

Lei *et al.* (2023) state that the plant genera *Phragmites*, *Typha* and *Juncus* are a good mix for pollutant removal which is important when looking at the criteria of being able to form a polyculture. A mix of different plant species can improve not only aesthetics but also ecological diversity. The latter can improve the resilience and general functionality of the biodevice since different species can target different pollutants or perform well under different conditions (Colares *et al.*, 2020).

The details on the plant species show why they were chosen as integral constituents of the floating device. They have the capability of improving water quality by reducing nutrients and removing a wide range of pollutants. Effective management of the chosen plants is important to maximize the efficiency of the device. They have to be harvested regularly to prevent older plants from releasing decomposing biomass back into the water and thus undoing parts of the phytoremediation benefits. (Colares *et al.*, 2020).

The biomass from the harvested plants could be used to feed livestock, produce energy or fertilization. As it was stated by Colares *et al.* (2020), such sustainable applications add value to the maintenance procedure.

How the three materials described so far were put together to form the biodevice can be followed in the next chapter which explains the construction process step by step.

3.4 CONSTRUCTION PROCESS

The beginning of the construction process was marked by a number of different possibilities trying to conjugate the use of natural materials, with durability, simplicity and easy biodevice

maintenance. Various ideas were proposed, some of which made it to the final design, while others were tested and dismissed either because they were impractical or would have resulted in an elevated workload that did would not have been justifiable through an increased usability. Overall, this phase was defined by very fruitful brainstorming sessions involving all stakeholders and with some try-and-error pre-tests that will not be illustrated in detail to avoid confusion. The following partly manual-styled depiction of the construction process presents the prototype design preferred by the team. More information on the other designs will be given in chapter 4.3.

It is important to keep in mind and understand that pieces of natural and almost unprocessed cork were used when looking at the following descriptions because it means that not only each platform but also each piece of cork is unique which results in a huge variability. The outlined construction process must be understood as a guideline on how to put together the different pieces and not as a precise engineering blueprint.

The pieces of cork were delivered on pallets (see Figure 15) and had a great variety of shapes and sizes (see Appendix E for a description of shapes and sizes).



Figure 15. Cork on pallets as delivered by producer (picture taken by author on 25.05.2022)

It was decided that it would be necessary to assort all the cork that was delivered and try to find a system to categorize them. It can be summarized that the sizes varied between pieces of around 10 cm x 24 cm and 42cm x 120 cm and that the categories could only serve as a very rough overview due to the immense variability in sizes and forms. For future building projects,

this step could probably be left out since it consumed a lot of time (around 3 days for 5 pallets) and there would probably be no knowledge gained by repeating it in further studies. The information obtained through this step can be seen in Appendix E. It does make sense to make two or three piles distinguished by overall piece size while unloading and building with pieces from one pallet at a time. If possible, big and rectangular pieces should be ordered. The thickness and more parameters of the cork will be described in chapter 4.2.

The first step of the construction process is to decide on the overall size of the floating platform constructed. It can be practical to divide the total amount of square meters into several platforms to minimize transportation problems and spread the different platforms across the water body. This also allows nutrient and pollutant uptake at different points in the lake. There is no ideal shape, and one might want to get creative and choose one for aesthetic reasons, but it is most likely easiest to aim for a rectangular shape. The manual building steps can be described as follows:

1. **Selecting cork boards:** The construction began with selecting cork boards, with a preference for larger boards with a rectangular shape to reach more square meters with fewer connections between the boards and more space for plants on each board.
2. **Laying Out the Boards** The chosen cork boards were laid out on the ground with an approximate distance of 5 to 10 cm between each board (see Figure 16). This part of the process is reminiscent of a jigsaw puzzle until the desired form and size are reached. Due to their natural forms, some boards might fit better next to each other than others.



Figure 16. Laying out cork pieces on land during construction process (picture taken by author on 26.07.2022)

3. **Positioning the Holes** All the boards were ordered with predrilled holes that turned out to be completely unusable without further work due to the ordered plants being much bigger than the holes (see Figure 17 left). To avoid this step completely, the plants should have been examined before ordering the cork to then give better instructions regarding the hole size to the cork provider. To find a good hole(s) size and positions, the plastic pots the plants were delivered in were held against the cork boards at locations that seemed suitable, and marks were drawn with a permanent marker (see Figure 17 right). The plants used in this project were delivered in a rectangular prism-shaped plastic pot with a size of 8.5cm x 8.5cm at the top and a height of 11cm. Attention was given to ensuring that the holes were adequately spaced and not too close to the edges of the boards. This precaution was necessary to prevent the formation of thin straps of material between holes, which could easily break under stress.



Figure 17. Positioning the Holes: Comparison plant size to predrilled hole (left) and marking size and position of improved plant holes (right) (Picture taken by author on 12.07.2022 and 24.11.2022, respectively)

4. **Cutting holes for the plants:** In the beginning of the biodevice development the predrilled holes were enlarged trying a variety of tools which was a very inefficient approach. At a later development stage, a jigsaw set at a 30° to 45° angle (see Figure 18) with a long wood-cut blade was used to cut the holes in the remaining cork boards. This approach ensured precision and accommodated the plant sizes. Thanks to the angle of the jigsaw, they had a conic form (visible in Figure 19) which prevented the

possibility of the plants slipping through the holes while giving their roots more than enough space to reach into the water.



Figure 18. Jigsaw calibrated with angle (Picture taken by author on 24.11.2022)



Figure 19. Small board with finished holes for plants (Picture taken by author on 22.11.2022)

- 5. Rope (ends):** Roughly 30cm to 40cm long pieces of the 3mm rope (see chapter 3.3.1 for details on rope) were cut off from their roll. To seal them the ends of the ropes were partly fused for one to two seconds to prevent fraying. A blowtorch was used to efficiently seal multiple ends simultaneously. The result is visible in Figure 20.



Figure 20. Rope end after being sealed with blowtorch (Picture taken by author on 24.11.2022)

6. **Using cork cubes as distance holders:** To prevent the boards from stacking on top of one another when floating, cork cubes were used to act as distance holders. At first 5cm x 5cm cubes were cut out of boards that had damages. Later in the process, these cubes were made from the pieces cut out for the plant holes which seems like a much more efficient approach. Each cube was perforated once in their middle with a 6mm wood drill (see Figure 21).



Figure 21. Perforating distance cubes with wood drill (Picture taken by author on 26.07.2022)

7. **Assembling the boards:** Different boards were connected using the rope pieces and cork cubes. The rope was threaded either through specifically drilled holes or, at times, through the holes cut for the plants. It was then guided through the cork cube and tied with a knot (see Figure 22 left & right). Connections were made in each direction of each board to create a flexible yet well-connected mesh of cork boards. This approach ensured that the structure remained cohesive while allowing some movement to adapt to water conditions.



Figure 22. Connections: Finished mesh of cork boards with distance cubes (left) and Close up of distance cube, rope and knot arrangement (right) (Picture taken by author on 24.11.2022 and 24.11.2022, respectively)

8. **Transport to site:** This point of the building process is a good moment to transport it to the water body. Depending on the size it might be necessary to carefully fold the island once in the middle. At the lake it turned out to be useful to lay out a big plastic cover/ plastic tarp and place the cork mat on it (see Figure 23).
9. **Macrophytes-to-cork marriage** The plants need to be taken out of the (plastic) container they were delivered in and be put in the holes of the cork bark. In many cases, some soil or even roots must be removed for the plant to fit into the hole. If the hole is way too small for some reason it is also an option to cut a plant bale in half and use the two smaller pieces for two small holes. A depiction of this step can be seen in Figure 23.



Figure 23. Putting plants into holes in cork boards (Picture taken by author on 22.02.2023)

10. **Securing the structure to the anchoring line:** Thicker rope was used to go around three sides of the island and make a connection to the anchoring line. Thin rope was looped around the outside edges of the outlying cork pieces and then attached to the thicker rope. The idea is to distribute the potential pulling forces along several cork pieces and create redundancy in case one of the outside cork pieces breaks.
11. **Launch the island into the water:** The fully prepared (cork board mesh + plants + anchoring line) island can now carefully be put into the water. In this step the plastic tarp has been proven to be helpful since it can be slid over the ground into or right next to the water with the island on top of it. The traction between the island and the plastic tarp is lower than it would be against the ground.
12. **The anchoring** For the anchoring of the biodevice there are many different possible solutions. The chosen solution should try keeping in mind to distribute the pulling forces along several sides/points of the biodevice for example by going around three out of four sides. The chosen setup needs to have enough resistance to keep the device in place and to allow accessing the biodevice for maintenance. In Almancil, originally a concrete block with a metal grommet that was supposed to be an overground punctual foundation, but it had some minor damages, so it was repurposed. It is important to avoid sharp edges that could cut the rope over a longer time period. Another way to

keep the biodevice in place was to connect it with two fixed points at the shore. The rope connecting to the anchor should be long enough to not be under tension when the water has its highest possible level. Figure 24 gives an idea of one of the chosen set-ups.

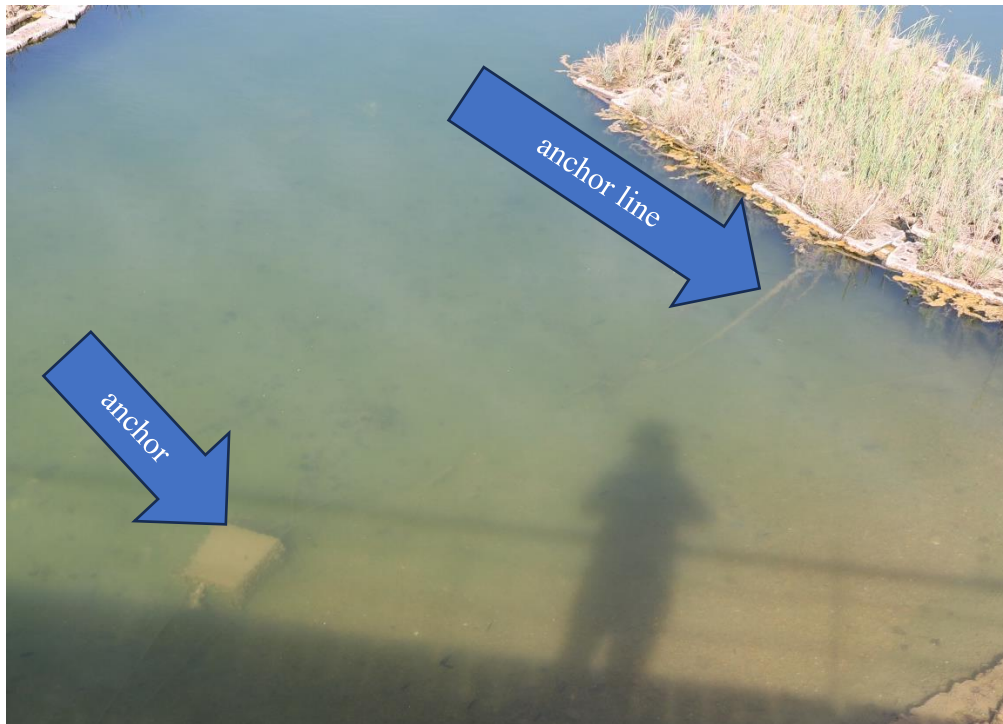


Figure 24. Island with anchor line & anchor block (Picture (adapted) taken by author on 22.09.2023)

The exact position of the anchoring lines and the threading of them can be requested at the *espaços verdes* (gardeners) team of the municipality of Loulé.¹⁰

The scheme of the finished biodevice and the discussion of the design can be found in the next chapter.

¹⁰ Final decisions regarding the anchor lines were made at the lake with a big number of changing ideas at very short notice and with the involvement of a large number of personnel, so that the author was no longer able to follow the exact course of events and lines due to the imminent language barrier. At least one of the biodevices is attached to the pillars of the bridge and the platform.

4

RESULTS, ANALYSIS AND DISCUSSION

This next chapter will present the results, analysis and discussion part of the dissertation to address the ROs described in chapter 1.1. After an in-depth examination of the water quality, the floating material of the biodevice cork will shortly be characterised before providing a detailed description of the biodevice. Finally, the flyer for dissemination to the broad public will be displayed.

4.1 EVOLUTION OF WATER QUALITY

The evolution of the water quality throughout the project is an essential parameter when it comes to evaluating the effectiveness of the biodevice. This subchapter describes the obtained water quality results, interprets them and discusses different factors that could have had an influence. In alignment with Research Objective 1 (RO1) it will be assessed whether there has been an improvement in water quality and which role the prototypes of the biodevice may have played in achieving this.

4.1.1 WATER QUALITY PARAMETERS AND TROPHIC STATE INDICES

Following the study design, water samples were collected in June 2022 and in June 2023 at the three points considered representative of the overall quality of the lake to assess the evolution in physical-chemical terms. A specific set of parameters was quantified using the analytical methods described in chapter 3.2. Furthermore, data from a previous project (Pimenta, 2021) on the lake was included in the assessment to get a long-term picture of the

water quality situation. Based on the data the trophic state index (TSI), which is an indicator for its ecological balance (see description in chapter 3.2), was calculated. The results are shown in Table 4.

Table 4. Water quality characterization results over the monitoring period of this (2022 & 2023) and previous (2019 & 2020 values from Pimenta (2021)) study

Parameter	26 Nov 2019 <i>from Pimenta (2021)</i> (Mean \pm SD*)	18 Feb 2020 <i>from Pimenta (2021)</i> (Mean \pm SD*)	17 June 2022 (Mean \pm SD*)	15 June 2023 (Mean \pm SD*)
<i>In-situ</i> temperature (°C)	16.2 \pm 0.1	18 \pm 0.4	26.8 \pm 0.23	26.4 \pm 1.32
<i>In-situ</i> pH (Esc. Sorensen)	7.2 \pm 0.4	5.5 \pm 0.3	6.6 \pm 0.16	7.4 \pm 0.06
<i>In-situ</i> dissolved oxygen concentration (mg.L ⁻¹)	--	--	9.0 \pm 0.1	10.3 \pm 0.35
<i>In-situ</i> dissolved oxygen saturation (%)	94 \pm 4	138 \pm 1	111 \pm 1	130 \pm 7
<i>In-situ</i> Secchi disk depth	0.48 \pm 0.11	0.63 \pm 0.21	0.67 \pm 0.25	0.70 \pm 0.23
Orthophosphates (PO ₄) (mg.L ⁻¹)	< 0.383 (LQ)*	< 0.383 (LQ)*	0.021 \pm 0.007	0.002 \pm 0.001
Ammonium (NH ₄) (mg.L ⁻¹)	< 0.12 (LQ)*	< 0.12 (LQ)*	0.05 \pm 0.007	0.020 \pm 0.006
Nitrates (NO ₃) (mg.L ⁻¹)	< 4.4 (LQ)*	< 4.4 (LQ)*	0.45 \pm 0.07	0.46 \pm 0.10
Nitrites (NO ₂) (mg.L ⁻¹)	--	--	0.002 \pm 0.001	0.002 \pm 0.001
Total nitrogen (N) (mg.L ⁻¹)	--	--	1.59 \pm 0.21	68.05 \pm 8.85

Parameter	26 Nov 2019 <i>from Pimenta (2021)</i> (Mean \pm SD*)	18 Feb 2020 <i>from Pimenta (2021)</i> (Mean \pm SD*)	17 June 2022 (Mean \pm SD*)	15 June 2023 (Mean \pm SD*)
Total phosphorus (P) (mg.L ⁻¹)	--	--	0.03 \pm 0.005	0.08 \pm 0.009
Chlorophyll <i>a</i> (mg.m ⁻³)	15 \pm 10	12 \pm 4	4.0 \pm 0.794	4.87 \pm 0.20
TSI (Chl-a)	54.40	51.97	40.05	42.17
TSI (TP)	--	--	37.42	53.34
TSI (TN)	--	--	62.39	126.03

*SD - Standard Deviation; LQ - Limit of Quantification.

The analysis of the data obtained at four different points in time (November 2019, February 2020, June 2022 and June 2023) reveals notable changes in the physico-chemical parameters as well as the trophic levels of the lake. The results suggest that there have been both seasonal fluctuations and long-term changes in water quality.

The water temperature shows an expected seasonal variation according to the atmospheric temperature on Winter (November 2019 and February 2020) or Summer (June 2022 and 2023) months. The lowest temperature was of 16.2 °C in November 2019, it rose to 26.8 °C in the summer of 2022 and reached similar values (26.4 °C) in 2023. The rise in temperature is typical and can have a strong influence on biological activity, namely the metabolism of microorganisms and the growth of vegetation (S. P. Singh & Singh, 2015).

In November 2019 the pH value was in the slightly alkaline range at 7.2, but dropped to 5.5 in February 2020 showing an acidic trend back then. Between the summer of 2022 and 2023 the pH values rose again (6.6 and 7.4), which could be connected with the implementation of the prototypes. The macrophytes most likely reduced dissolved CO₂ in the water through photosynthetic activity and therefore increased the pH value (Kaijser *et al.*, 2021; Sand-Jensen, 1983). The described hypothesis also fits the findings of the studies presented in chapter 2.5, especially Ghamary & Mohajeri (2021).

The oxygen concentration shows high values in both measurements (2022 and 2023), with the dissolved oxygen content increasing from 9.0 mg/L in June 2022 to 10.3 mg/L in June 2023. Oxygen saturation was also always elevated with 111 % (2022) and 130 % (2023). This means there was a rise after the implementation of the biodevice. The influence of water

temperatures on oxygen saturation levels can be consulted in Rajwa-Kuligiewicz *et al.* (2015) or Koue (2024) who intertwines IPCC climate change models and dissolved oxygen levels of a freshwater lake. Since both samples were taken at more or less the same temperature this factor can not be the explanation for the increase. Plants could be though since they carry out photosynthesis and produce oxygen during the day which they transport to the roots where it is released to the water. In the absence of light, their cells breathe and contribute to the removal of oxygen from water (Duarte *et al.*, 2021; Jespersen *et al.*, 1998; Woodward & Hofstra, 2022; L. Yin *et al.*, 2021). It seems as if the macrophytes introduced through the biodevice increased oxygen levels. Oxygen saturation also rose after the implementation of the previous biodevice between November 2019 (94%) and February 2020 (138%). The oxygen supersaturation shown in the results also indicates that the macrophyte vegetation has a high capacity for water oxygenation (Ayres *et al.*, 2022).

This lake has some variations in its depth, and it is important to check whether the light always reaches the bottom of the lake, to ensure that photosynthesis and therefore oxygenation can occur throughout all water column. Although, some authors (e.g. Department of Environment & Science Queensland (2018) consider that Secchi disc is not appropriate for use in shallow waters where it can be seen when resting on the bottom, there is no other standard methodology to verify the transparency *in-situ* whether light reaches the bottom of a lake with these characteristics. The transparency to the Secchi disc in 2022-23 was measured at points that were reachable from the shore and had depths between 0.5 m and 1 m. During the site visits to the waterbody after June, the observation of the author suggests that the water appeared consistently very clear and no signs of eutrophication. Although this observation cannot substitute for a reliable scientific evaluation, it should be seen as surveillance to prevent eutrophication phenomena and is very important in the lake's aesthetics, as part of the public park.

Phosphorus and nitrogen values show very different evolutions over time. In June 2022, total phosphorus (TP) was only 0.03 mg/L, indicating relatively low nutrient availability. In June 2023, this value increased slightly to 0.08 mg/L, which may have been caused by external inputs which will be described further in chapter 4.1.2. The amount of orthophosphates, the form of phosphorous that plants, as macrophytes and algae, can assimilate (Correll, 1998), decreased to a minimum after the implementation of the biodevice with 0.002 mg/L in 2023. The oxygen abundance could have an influence on the low P levels since (as described in chapter 2.5) phosphorus often remains bound in sediments under oxic conditions (Andersen

& Ring, 1999). Studies even suggest oxygenation as a remediation strategy for high P values (Prepas & Burke, 1997; Tammeorg *et al.*, 2017, 2020).

The values obtained for the inorganic nitrogen forms, ammonia, nitrites and nitrates, remain low, but total nitrogen concentrations increased from 1.59 to 68.05 mg/L, respectively in 2022 and 2023, certainly due to the increase of organic nitrogen, mainly related to the improper reintroduction of exotic species into the lake. The big gap between inorganic nitrogen compounds and total nitrogen confirms a high amount of organic nitrogen. Following the description in chapter 2.5 this increase could indicate an input of external nitrogen, possibly also due to urban runoff (Jani *et al.*, 2020), heavy organic inputs like leaf litterfall (Lusk *et al.*, 2020) or other human induced actions like the usage of fertilizer (Bijay-Singh & Craswell, 2021). This could indicate that nitrogen is mainly present in organic form and not immediately available for plant growth (N. O. G. Jørgensen, 2009; Søndergaard *et al.*, 2017; Yao *et al.*, 2018).

Chlorophyll *a* concentrations show a decrease in the period from 2019 to 2023 which shows water quality improvement. In November 2019, the value was 15 mg/m³, dropping to 4.0 mg/m³ in June 2022 and rising slightly to 4.87 mg/m³ in June 2023. This indicates that algae growth has been stabilised which corresponds with the low values obtained for ammonia, nitrates and orthophosphates, (Lewis *et al.*, 2011).

As described in chapter 3.2 the trophic state of the lake was assessed using the trophic state index (TSI) according to Hu *et al.* (2014). In November 2019 and February 2020, due to laboratory restrictions (high quantification limits for TN and TP) the classification was based solely on the chlorophyll *a* value, resulting in TSI (Chl-*a*) values of 54.40 and 51.97, indicating slightly eutrophic conditions. In June 2022, the lake showed more oligo-mesotrophic conditions with a TSI (Chl-*a*) of 40.05, while the TSI values for TP (37.42 = oligo-mesotrophic) and TN (62.39 = moderately eutrophic) indicate a non-uniform nutrient ratio. The increase in total nitrogen content in June 2023 led to an extremely high TSI(TN) value of 126.03, which suggests hypereutrophic conditions, although the chlorophyll values (TSI (Chl-*a*) = 42.17) continue to indicate mesotrophic conditions. This discrepancy indicates a nutritional situation in which nitrogen is present in excess (high total N) but is not converted into biomass, because it is not bioavailable for plants. Similar situations could be observed in other recent and not-so-recent studies (see for example: Elser *et al.*, 1990; Litchman *et al.*, 2003; Maberly *et al.*, 2020; Sterner, 2008). A key point is that the total nitrogen (TN) measured includes both inorganic (NH₄⁺, NO₃⁻, NO₂⁻) and organic (e.g. proteins, amino acids and urea) nitrogen compounds. If organic nitrogen compounds predominate in the aquatic system they

lead to a high total nitrogen value, while the concentrations of inorganic compounds remain low. This is -as described in chapter 2.5- because the organic nitrogen must first be converted into ammonium (NH_4^+) through the ammonification process. A delayed or slow ammonification process can cause the nitrogen to remain in organic form and not be detectable in NH_4^+ , NO_3^- or NO_2^- measurements (Follett, 2001; Sauer *et al.*, 2001).

Total phosphorus (TP) values also play an important role in interpreting nitrogen distribution. The already mentioned total phosphorus content and additionally the orthophosphate (easier availability for plant uptake) values in the measurements are comparatively low, which indicates phosphorus limitation. If the ratio of nitrogen to phosphorus is too high, this can lead to an accumulation of nitrogen in the system since phosphorus is the limiting nutrient for algae growth. In such cases, the nitrogen is not utilised and accumulates as total nitrogen, while the inorganic nitrogen compounds are not consumed in large quantities by the algae due to the low availability of phosphorus (Litchman *et al.*, 2003; Maberly *et al.*, 2020). This leads to a situation where TN is high, while NH_4 , NO_3 and NO_2 do not increase significantly (Bhateria & Jain, 2016).

The low chlorophyll *a* content also supports the nutrient limitation hypothesis. Chlorophyll *a* is a direct indicator of algal biomass in water bodies (Tao & Yu, 2024). The low levels of chlorophyll *a*, despite the high concentrations of total nitrogen, may indicate that the available nutrients are not being effectively utilised for algae growth (Filstrup & Downing, 2017). Moss *et al.* (2013) had similar findings in shallow lakes which supports the hypothesis.

Overall, the results of the measurements lead to the conclusion that the high values of total nitrogen, with simultaneously low concentrations of ammonium, nitrate and nitrite, indicate an imbalance in the nitrogen cycle. Delayed conversion processes in the nitrogen cycle and nutrient limitation, particularly phosphorus, could be other reasons for the low chlorophyll *a* values.

Which other factors could have had an influence on the discrepancy in values is subject of the next chapter.

4.1.2 FAUNA AND OTHER INFLUENCING FACTORS

During the site visits after June 2022 the presence of turtles and fish, not yet further characterised but potentially exotic, began to be visible. In June 2022 there was no imminent sign of the presence of fish or turtles. It remains unclear whether they were not noticed, the visibility was not good enough to see them or if they were not yet present. The removal of exotic species in 2021 (see chapter 3.1.3) might or might not have resulted in all the turtles and fish being removed but must have decimated them to a minimum. Even though no exact scientific measures were undertaken to describe or observe the populations growth, it was clearly visible that until the last visit in September 2023 the number and size of the animals had considerably risen. Figure 25 shows two of the many turtles in the lake on the edge of one of the prototypes.



Figure 25. Biodevice prototype design 4 with two turtles (Picture taken by author on 22.09.2023)

The aquatic fauna in the lake in Almancil has not been assessed in detail due to the limitations of time and resources. To interpret the results described in chapter 4.1.1 there is however a sufficient pool of literature to formulate some basic hypotheses about the possible effects of aquatic fauna on the water quality and nutrient cycle (which can be strongly connected with the total nitrogen value).

It is likely that the (presumably exotic) spotted aquatic animals introduce (complex) nitrogen compounds and phosphorus into the water via their faeces and through decomposition (see for example Chen *et al.*, 2013; Halvorson & Atkinson, 2019; Kajimura *et al.*, 2004; Lee

et al., 2006; Nędzarek *et al.*, 2015; Song *et al.*, 2015; Sterrett *et al.*, 2015; Thayer *et al.*, 1982; Yavuzcan Yildiz *et al.*, 2017).

A literature survey by Halvorson & Atkinson (2019) demonstrates that aquatic animals have an important impact on nutrient dynamics in water bodies through egestion (e.g., faecal particulate matter) and excretion (e.g., dissolved ammonium and phosphate). The meta-analysis states that egested materials often include organic matter with high nutrient content which is processed by microbial decomposition into available forms of the nutrient cycle. More immediately bioavailable forms of nutrients enter the cycle through excretion. The literature survey describes egestion and excretion across 47 freshwater animal species and 215 study populations and could be a good starting point for future research once the exact animal species in the Almancil lake are assessed.

Kajimura *et al.* (2004) studied nitrogen excretion of teleost fish (specifically rainbow trout) which mainly excrete ammonia and urea but also nitrogenous end products for example amino acids and proteins. The study mentions those two biomolecules together reach up to 21% of the total nitrogen along with a bigger share of ammonia-N (53-68%) and urea-N (6- 10%). Urea-N as a value was not assessed separately for the lake in Almancil so being an organic chemical with high nitrogen content (Amaya-García *et al.*, 2024) it is represented as part of the total nitrogen value. Since the amount of urea-N was not measured with a separate method, for example, the diacetyl monoxime method (Langenfeld *et al.*, 2021), it remains unknown how much of the increase in total nitrogen between 2022 and 2023 was due to urea-N.

The decomposition of aquatic animals is another important source of organic nitrogen and phosphorus in aquatic ecosystems. Nędzarek *et al.* (2015) state that organic nitrogen and organic phosphorus accounted for 94 and 54 % of TN and TP release, respectively, when they studied the decomposition of *Notothenia coriiceps*. Even though the study was performed in salt water at around 0°C it indicates that decomposition could be an important part of the elevated total nitrogen values in 2023. Sterrett *et al.* (2015) describe a high phosphorus content in turtle skeletons which constitutes a big portion of their body mass. While they also state that the phosphorus excretion rates are lower compared to other vertebrates like fish, they still represent a large standing stock in freshwater environments. It is not unlikely that this phosphorus is also released into the water body when the turtles decompose though this particular point seems to be underexplored in literature (Wenger *et al.*, 2019). There could be a connection between the slight increase of total phosphorous in the Almancil lake and the excretion and decomposition of turtles.

Literature about aquaculture effluent (e.g., Song *et al.* (2015) & Tabrett *et al.* (2024)) shows that fish can be responsible for high concentrations of nitrogen and phosphorus in water. This is primarily due to animal excreta and residual organic matter, reinforcing the role of faecal and decompositional contribution to nutrient loads.

Another scientific field that examines the relation of fish faeces and excreted ammonia with plant uptake of nutrients is aquaponic systems. Yavuzcan Yildiz *et al.* (2017) for example assesses the critical role of water quality and nutrient cycling in balancing fish health and plant growth mentioning a lot of detailed parameters and their consequences for plant and fish health.

As described in chapter 3.1 the lake in Almancil is rather small and artificial so there are similarities to aquacultural installations and aquaponic systems. The effects could even be stronger especially since there is no or little N or P extraction through fishery (Boros, 2022) other than the removal action day in 2021 (see chapter 3.1.3).

When it comes to the turtle population spotted in the lake it also has to be taken into consideration that, depending on the species, turtles can consume vast amounts of plant material which is then released into the environment with a high total nitrogen value mainly consisting of ammonia-N as well as organic nitrogen in form of faeces and urea (Chen *et al.*, 2013; Ip *et al.*, 2012; Lee *et al.*, 2006; Song *et al.*, 2015; Thayer *et al.*, 1982). Exactly what and how much the turtles in Almancil ingest has not been established, but it can be assumed that the biodevice is affected in some way. The ingestion of large quantities of plant material would be a direct shortcut in the conversion of nitrogen bound in plants to organic but also inorganic nitrogen, similar to what is described by Thayer *et al.*, (1982)¹¹. It could be that the organic nitrogen also contributes to the unaccounted part of the increased total N value while the turtles simultaneously decrease available macrophyte phytoremediation capacity by nutritional intake.

¹¹ The study is from 1982 but still being used for recent publications, see for example Seminoff *et al.* (2021). It seems as if there is scope for new research in this field.

Based on the described processes an interim conclusion could be that the observed increase in population and size of the aquatic animals had an influence on the very high levels of total nitrogen in 2023.

In addition, other external inputs of nitrogen could also play an important role. Fertilisers for the park around the lake, maintenance work or the input of urban pollutants through rain would be well-studied reasons. If fertilisers had been applied in or around the lake, macrophytes had been cut (less filtration capacity) or if it had rained (urban runoff with high nutrient loads) shortly before the measurement in 2023, this would be a very plausible explanation for the increase in total nitrogen values (Bijay-Singh & Craswell, 2021; S. Wang *et al.*, 2022). In a dataset kindly provided by IPMA from the Faro weather station for June 2023¹², it can be seen that there was no notable rainfall before the measurement. Loulé's Director of Green Spaces (Mário Ferreira) stated that no maintenance work on the prototype has been undertaken between June 2022 and June 2023 and considers it highly unlikely that his colleagues in the parish of Almancil are fertilising the areas around the lake¹³. These three pieces of information make the 'classic' external nitrogen inputs described unlikely. The occasional Sahara dust storms in the Algarve could have been a unique explication for the increased total N values if the dust contained any forms of nitrogen which doesn't seem to be the case (Vanderstraeten *et al.*, 2008). It, therefore, is not worth assessing rather the dust storm in the east of Spain on the 11th of July also reached the Algarve (IQ Air, 2023).

Another hypothesis could have been that pieces of natural cork negatively influence the water quality due to deterioration or dissolving when exposed to water over a longer period of time. The current state of research has a gap here and therefore does not allow a clear position to be taken. It might however be interesting to verify this point in further studies. Testing if the aquatic animals eat parts of the cork and then release the nutrients taken up from the cork into the water could be an additional question worth assessing. The study about floating wetlands made out of agglomerated cork at the marina in Porto (Calheiros *et al.*, 2020) cannot

¹² The original dataset is 17 pages long and is therefore not included in this dissertation, but the author can provide a copy upon request.

¹³ Information requested and obtained via text message on 27 September 2024.




be regarded as an invalidating point, since the biodevice used in Almancil is made out of natural cork pieces.

4.2 CORK CHARACTERIZATION

The properties of the material cork were the reason for choosing it as floating material for the developed biodevice but not the main focus of this dissertation. The characterisation in this subchapter is therefore concise, but more information can be found in literature, for example Gil (2015) and Pereira (2007c).

The cork material tests described in chapter 3.3.2 led to results presented in Table 5:

Table 5. Cork characterization results

Parameter	Result	(mean \pm standard deviation); n = 30
Colour (L, a, and b represent colour values in the CIE-Lab colour space)	Exterior	L: 25.89 \pm 4.63
		a: 5.10 \pm 1.18
		b: 7.50 \pm 1.94
		Lateral
		a: 12.46 \pm 1.13
		b: 18.06 \pm 1.32
		Interior
		a: 6.76 \pm 2.49
		b: 11.59 \pm 2.29
Texture		The cork samples studied presented a hardness of 251.30 \pm 15.10 N.
Density	The tested samples showed a density of 199.6 \pm 25.97 mg/cm ³ (mean \pm standard deviation).	
Average thickness	5.95 \pm 6.89 cm, based on measuring the 30 cubes from 10 different boards	

When comparing the values obtained for this dissertation against the values of a study by Paulo & Santos (2023) about virgin (first harvest ever) and secondary cork (following harvests) quality there are some similarities and some differences. The “interior” (called “Belly” in the cork quality study) L* values (44.01 ± 9.77) showed similar values to the low-quality category for both virgin cork (43.52 ± 3.90) and secondary cork (43.95 ± 3.59) which indicates comparable lightness. The values for a* and b* differ substantially with the a* value (6.76 ± 2.49) being notably lower than the values for low-quality virgin cork (11.22 ± 1.32) and secondary cork (12.68 ± 1.70) and the b* value (11.59 ± 2.29) being much lower than the values for low-quality virgin cork (27.57 ± 2.74) and secondary cork (27.57 ± 3.79).

The “exterior” (called “Back” in the cork quality study) L* value (25.89 ± 4.63) of the sample is notably lower than the low-quality category for both virgin cork (38.65 ± 4.53) and secondary cork (30.16 ± 4.07) which indicates a darker cork surface. The a* value (5.10 ± 1.18) is much higher than the values for low-quality virgin cork (2.89 ± 0.72) and secondary cork (3.10 ± 0.86) which indicates a stronger red component. The b* value (7.50 ± 1.94) is lower than the low-quality virgin cork (11.90 ± 2.84) and secondary cork (8.23 ± 1.83) values from the comparison study which is a sign of reduced yellow intensity. The “lateral” side of samples measured in this study has no clearly corresponding counterpart in the study by Paulo & Santos (2023).

The differences in colour could be explained by the long storage time of the cork pieces used for the biodevice under the open sky or by the fact that Paulo & Santos (2023) sandpapered their samples before measuring them. The comparison with their study gives an indication towards the suggestion that the cork bought for the biodevice might have low quality.

The cork samples studied had a hardness of 251.30 ± 15.10 N (mean \pm standard deviation). It should be noted that cork can be compressed to about half its width without losing any flexibility and recovers its shape and volume as soon as it stops being pressed, being the only solid material that, when compressed on one side, does not increase in volume on the other (Pereira, 2007b, 2015; Sergi *et al.*, 2021).

Chorana *et al.*, (2019) state that cork has an average density of 256.77 kg/m^3 ($= 256.77 \text{ mg/cm}^3$) which is higher than the value obtained in this study.

Anjos *et al.* (2014) performed a series of tests on cork planks collected “*after the post-harvest water boiling operation and air drying*” which is the step after which the cork boards for the prototype were purchased. According to their research design the samples taken for this study can be categorised as “high density ($0.19\text{-}0.25 \text{ [g/cm}^3\text{]})$ ”.

The buoyancy/load capacity of water-soaked cork was not tested with laboratory methods as described in chapter 3.3.2. It was possible to observe that the surface of the piece was still over the water with a weight of 3 kg and fully submerged (though not sunk to the bottom) with a 4 kg load. So according to this the load capacity of cork that is (partly) soaked with water lies somewhere between 9.02 kg and 12.03 kg per m² cork (at 6 cm thickness which is close to the value of the average height of the boards used in the project (see Table 5). As mentioned before the value can only be seen as a rough estimate.

In which ways the pieces of natural cork were connected and how they formed the biodevice is described in the next section along with an assessment of its structural functionality.

4.3 ASSESSMENT OF THE STRUCTURAL DESIGN(S)

Four different design types of the prototype were developed because of the varying concerns and ideas of different stakeholders. The main idea of using cork as the buoyant carrier material for macrophytes is identical. The construction process in chapter 3.4 describes the making of design one, the original idea and the favourite of the stakeholders from the UAIG since it uses fewer different materials. A scheme summarizing the most important aspects of that favoured design one is shown in Figure 26.

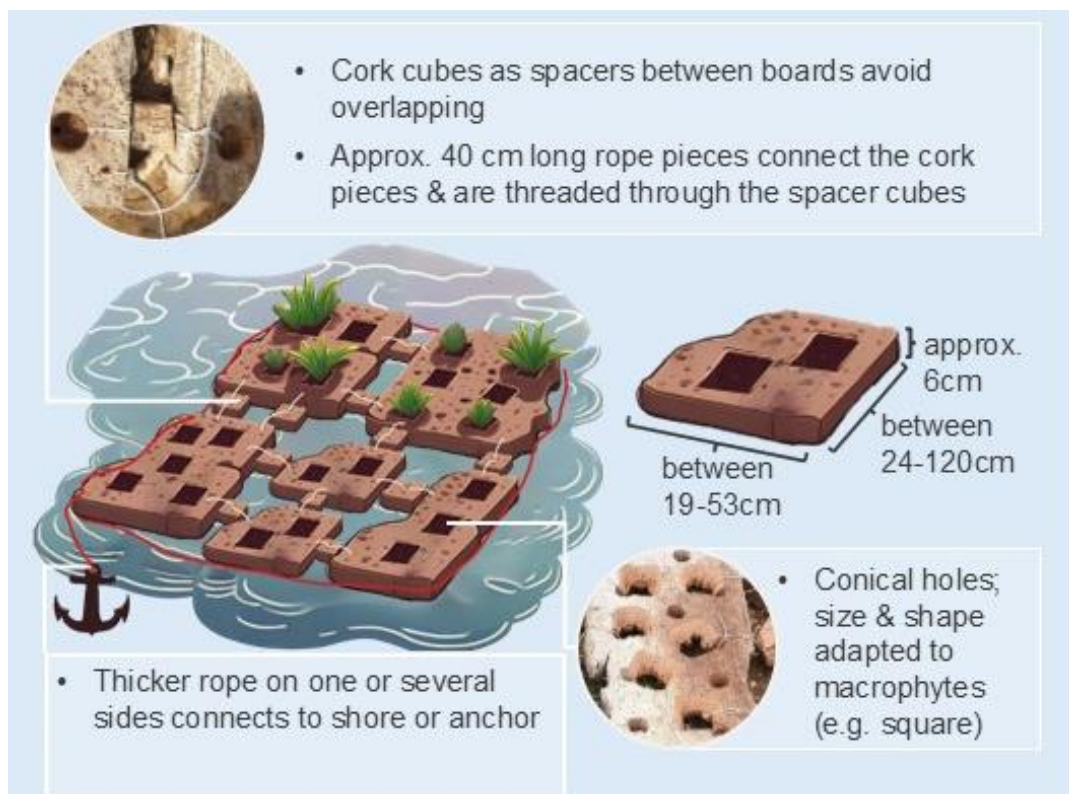


Figure 26. Scheme of biodevice (idea & content by author; design by Leon Kanigowski)

The four prototype designs were placed in the lake at three strategically chosen locations (see Figure 27 (two of the designs were connected with each other by using the same anchoring line)) to counterbalance potential stratification of the water column and to allow them to be pulled to the shores, facilitating the necessary maintenance operations on the plants and some components (cut plants and replace cork boards if necessary).

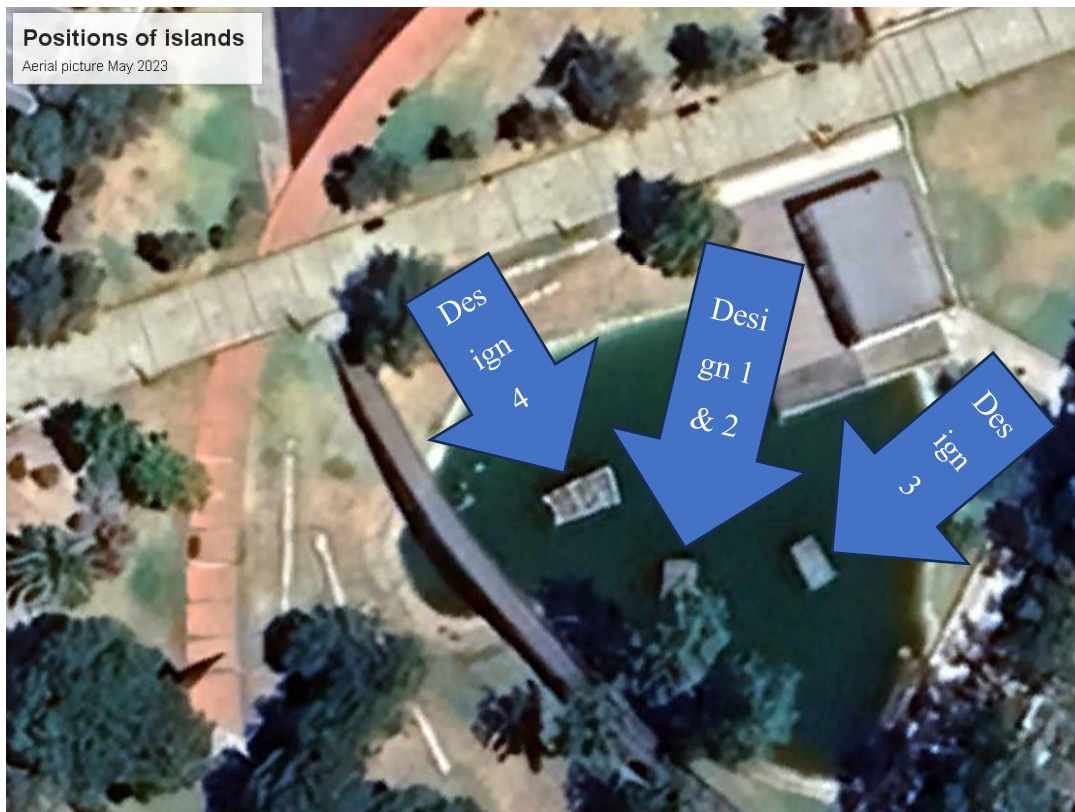


Figure 27. Satellite image of the lake in Almancil with visible prototype positions (adapted) (GoogleEarth Pro (Desktop), 2023)

Due to the different sizes and shapes of the boards explained above it is not feasible to try and find a 100% consistent/ precise number of boards per square meter or similar. It is crucial to understand the underlying idea and system to be able to reproduce the design. Rough estimates of numbers will be given wherever possible.

As seen in Figure 16 and described in the last chapter the pieces of natural cork were laid out next to each other and their positions were changed until the desired shape of the island was achieved. The more rectangular and bigger the pieces are, the easier it is to quickly reach a big island while reducing the number of necessary connections between them. The length of the rope between the cork pieces should be tight enough to keep them in place but long enough to allow movement for example through waves.

Long and narrow pieces turned out to be prone to breaking after the holes were cut because only thin “bridges” were left around the holes.

The number of holes/plants depends on a lot of factors which so far cannot be calculated with certainty but only estimated. The biggest concern when calculating the number of plants is that the load on the cork pieces might get too high and let them sink.

At this stage of the research, we can only estimate numbers for the following factors:

- **The buoyancy/load capacity of water-soaked cork** (described in chapter 3.3.2 & 4.2)
- **The weight of the plants** changes over time as the plants grow. Also part of the plants are under water which influences the forces on the cork boards. The weight can be controlled a little bit by cutting the plants. The growing weight of the plants and how they affect the biodevice needs to be a subject for future research.

It is best to select a conservative approach when it comes to the number of plants per cork board/m². Often the number might also be restricted to assure the stability of the board and avoid ruptures, meaning that if there are too many holes too close to each other (or the edge) the boards tend to break more easily.

A short overview of the different designs and their pros and cons will be described in the following Figures 28 to 32 and tables 6 to 10:

Design 1:

Materials: cork and rope with cork cubes to keep distance between pieces, macrophytes



Figure 28. Island design 1 in water (picture taken by author on 22.09.2023)

Table 6. Advantages & disadvantages of design 1

Advantages	Disadvantages
<ul style="list-style-type: none"> - only cork and rope are used as materials - individual sizes and shapes possible - possible to change individual pieces of cork if necessary (maintenance) - most aesthetic - closest to the original plan by UAlg stakeholders 	<ul style="list-style-type: none"> - can be difficult to transport - lots of work time due to the number of connections that need to be tied - every knot is a potential source of problems if not done correctly - might be fragile to influence from storms etc., when being pulled to the shore or in locations with a strong current - more worktime at water body because the plants need to be put in there

Design 2:

Materials: cork, macrophytes, wooden logs (scrap wood) as frame interconnected with rope (knots), macrophytes and extra cork connected to wooden logs to increase buoyancy



Figure 29. Island design 2 in water (picture taken by author on 22.08.2022)

Table 7. Advantages & disadvantages of design 2

Advantages	Disadvantages
<ul style="list-style-type: none"> - more robust - quicker to build than design one - impossible for cork pieces to slip onto each other - easier to transport (fits on a truck with crane) than design 1 & 4 - easier and quicker to put in water - wood is being reused - possible to put plants into holes prior to transport to the water body - possible to change individual pieces of cork if necessary (maintenance) 	<ul style="list-style-type: none"> - one more different material - wood might rot before cork - the wooden logs absorb water and become so heavy they would sink without additional cork pieces added for buoyancy - the extra floating corkboards work but look bad when in the water - wood pulls down the cork boards with plants



Figure 30. Island design 2 being deployed by crane (picture taken by author on 22.08.2022)

Design 3:

Materials: wooden planks (part of no longer needed delivery frame/pallets) cork underneath and above , everything held together and in place with rope, macrophytes



Figure 31. Island Design 3 being deployed in "the traditional way" due to crane defect (picture taken by author on 25.10.2022)

Table 8. Advantages & disadvantages of design 3

Advantages	Disadvantages
<ul style="list-style-type: none">- robust- impossible for cork pieces to slip on top of each other- quicker to build than design 1 & 2- easier to transport (fits on a truck with crane)- easier and quicker to put in water than designs 1 & 4- reuse of old wood- easy and very safe connection to anchoring line	<ul style="list-style-type: none">- one more different material than design one- wood might rot before cork- looks worse than versions 1 and 2- wood is relatively thin and fragile

Design 4:

Materials: cork and rope with cork cubes to keep distance between pieces, macrophytes, cork boards without plant holes as edging strip (no cubes or distance between them)



Figure 32. Island Design 4 in the lake (picture taken by author on 22.09.23)

Table 9. Advantages & disadvantages of design 4

Advantages	Disadvantages
<ul style="list-style-type: none">- only cork and rope- individual sizes possible- possible change individual pieces of cork if necessary (maintenance)- (objective was) easier maintenance and higher stability than design one	<ul style="list-style-type: none">- can be difficult to transport- lots of work time due to the number of connections that need to be tied- every knot is a potential source of problems if not done correctly- no space between edging parts and therefore more likely for the pieces to slip onto each other- more worktime at water body because the plants need to be put in there

These four designs were placed in three different locations in the lake (see Figure 33) with designs one and two being connected to each other by sharing the same anchor line.

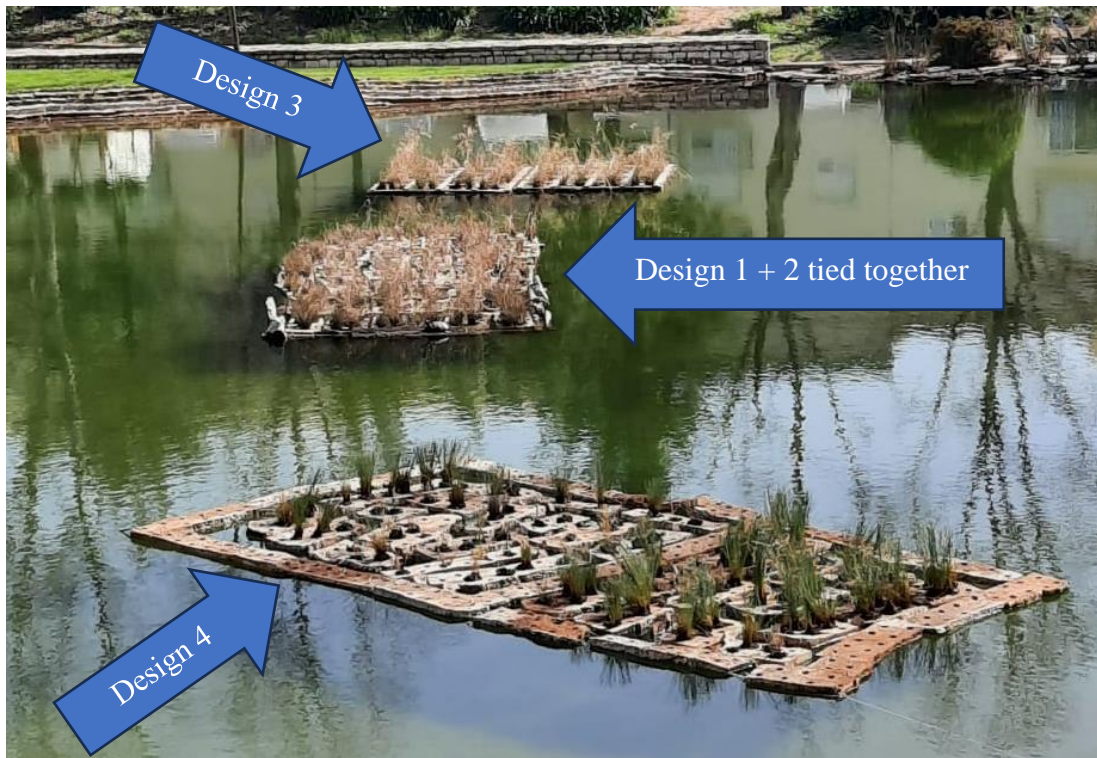


Figure 33. All designs in the lake (Picture taken by Mario Ferreira on 22.02.2023 and adapted by author)

Table 10 shows the sizes and number of plants of each island and summarizes them into one total.

Table 10. Sizes and plant numbers of different designs

Design Nr.	m ² (length x width)	Number of cork boards (and wood) used	Number of plants
1	11.37 (4.03 x 2.82)	28 pieces of cork with plant holes	218 but the holes are smaller, so the plants were cut in half → 109 entire plants
2	5.36 (1.90 x 2.82)	12 pieces of cork with plant holes + 10 around the frame (5 wooden logs)	55 entire plants
3	8.30 (2.10 x 3.95)	27 (40 wooden boards that came from a pallet)	136 entire plants

Design Nr.	m ² (length x width)	Number of cork boards (and wood) used	Number of plants
4	16.47 (5.40 x 3.05)	17 pieces of cork with plant holes + 15 for the frame without plants	57 entire plants
Total	41.50	109	357 entire plants

The required total size of constructed floating wetlands was estimated with 10% of the lake size in the beginning and later reduced to 5% because the turbidity system in place (see chapter 3.1.3) also contributes to an improved water quality¹⁴. Literature suggest that there are all kinds of possible sizes for CFWs (Bi *et al.*, 2019; Hartshorn *et al.*, 2016; Lucke *et al.*, 2019; Oddsson *et al.*, 2021; Pavlineri *et al.*, 2017). In a study by Hartshorn *et al.* (2016) three stormwater ponds were equipped with CFWs covering areas between 5% and 7% for each pond. Table 10 shows that the combined size of the prototypes is 41.5 m² which corresponds to 3.46% of the total size of the lake in Almancil (1200 m²). After the deployment of the prototype design 4 in February 2022 the stakeholders agreed to assess the effectiveness of the biodevice before deploying more platforms. The reasons were mainly practical, for example more plants would have had to be ordered to make more platforms. The Table 11 provides an overview of some averages based on Table 10:

¹⁴ The initial estimation and decision to decrease that value was made by the head of the project at the ISE-UAlg.

Table 11. Average boards/m² & plants/m²

Design Nr.	Average number of boards per m ²	Average number of plants per m ²
1	2.46	9.59
2	4.1	10.26
3	3.25	16.39
4	1.94	3.46
Combined average	2.94	9.93

According to Table 11 we can see that one square meter averagely consists of three corkboards. There are approximately ten plants per square meter. These values can only give an indication since we are working with a natural product, and the size of boards varies (see Appendix C for an overview of corkboard shapes and sizes). Also, if the plants are smaller, it is possible to put more plants on each board (like in design one). The results in Table 10 & Table 11 above lead to some conclusions:

- Design 3 is the most compact and able to support the biggest number of plants per square meter which can be especially useful in small spaces.
- Design 2 and 4 need more cork than design 3 and 1 and thus require more resources.

In the development and testing of the floating wetland biodevice, various practical considerations were included, all aimed at maximizing performance and stability while allowing maintenance. One example of this was using cork cubes as spacers to prevent overlapping of the cork boards. Initial intents for these cubes were meant to space the boards so that they did not stack on top of each other, particularly when pulling the device in and out of the lake. It was, however, noted that soaked cork boards are heavy and float deep in the water, making it less likely to have overlaps, at least in the calm water conditions in the lake in Almancil.

After deploying the prototypes, they should be monitored and if necessary maintained.

In this regard, Ayres *et al.* (2022) note that

“The design of a CFW system should consider harvesting as a key component of maintenance and ensure it is able to be conducted safely and efficiently” (Ayres *et al.*, 2022).

All the versions were designed keeping this key principle in mind. In terms of robustness, design three achieved the highest ranking, but all of the platforms can be moved through the water by pulling the anchoring lines gently and patiently. Other aspects of maintenance were discussed in Table 6, Table 7, Table 8 and Table 9.

Due to the increase in weight over time in the water, it is very questionable if any of the designs could be removed completely without damaging them (e.g. to place them elsewhere).

This assumption is based on the fact that already during the construction process care had to be taken while handling big boards to not break them. Especially once the plants were put in the holes the material broke on a few occasions while being carried because of the extra weight.

Design two does not seem to be a good solution because it seems as if the wood logs are so heavy after being soaked with water that they need a lot of extra cork as buoyant material to stay afloat and not drag the actual boards with plants under water (see Figure 34).

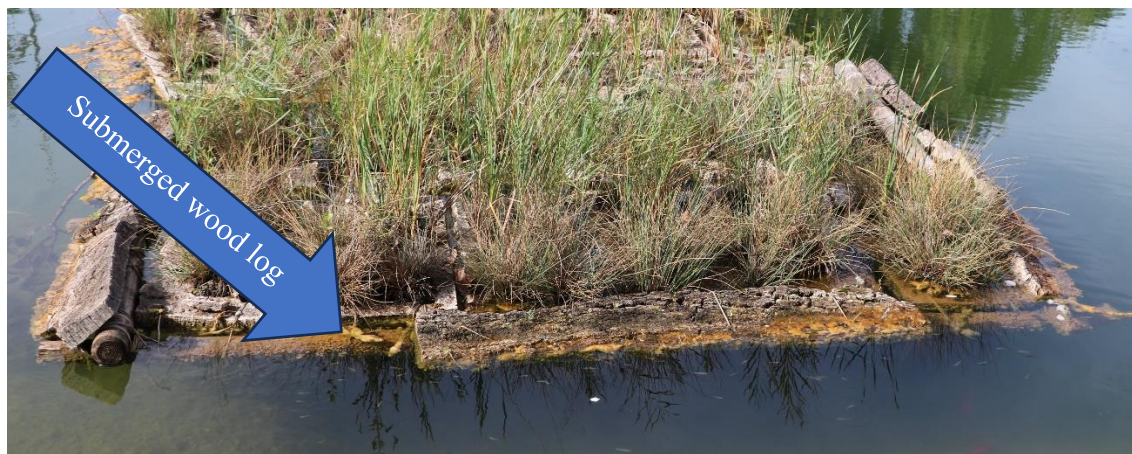


Figure 34. Wooden log submerged potentially due to water intake (Picture taken and adapted by author on 22.09.2023)

The developed structure resembles minimum two commercial CFWs that also use cork as a floating material (Alhárabe, 2021; Bluemater, n.d.). The difference to the device used prior to this study in the lake in Almancil produced by Bluemater is still remarkable since the current biodevice uses pieces of natural cork and connects the pieces by rope and not puzzle like connector pieces (Bluemater, n.d.). A similar biodevice from Spain uses natural cork but connects the pieces with some kind of a metal cage/mesh (Alhárabe, 2021). None of the two comparable devices seems to use conical holes for the plants.

The next pages show some of the results regarding the developed biodevice in Almancil condensed into a short flyer.

4.4 FLYER ABOUT BIODEVICE

The flyer mentioned in RO3 could resemble the following draft. An editable file was made available to the head of the project at the ISE-UAAlg via email on 30.10.2024. The actual dissemination of the material to other municipalities has not been undertaken by the author because it was not within his scope of responsibilities. The provided flyer enables to quickly explain the idea of the device and could be used during meetings and events, for example by different municipalities along the Algarve (and other parts of the world). If a use case of the biodevice ever happens to be somewhere else than the Algarve the choice of plants mentioned on the flyer would have to be double-checked to confirm they are still autochthonous and not invasive. In combination with chapter 3.4 of the dissertation, other stakeholders can also rebuild or adapt the biodevice for their needs. The flyer is presented in English and Portuguese to take account of the localised nature of the planned area of use.

Success Story:

Jardim das Comunidades, Almancil

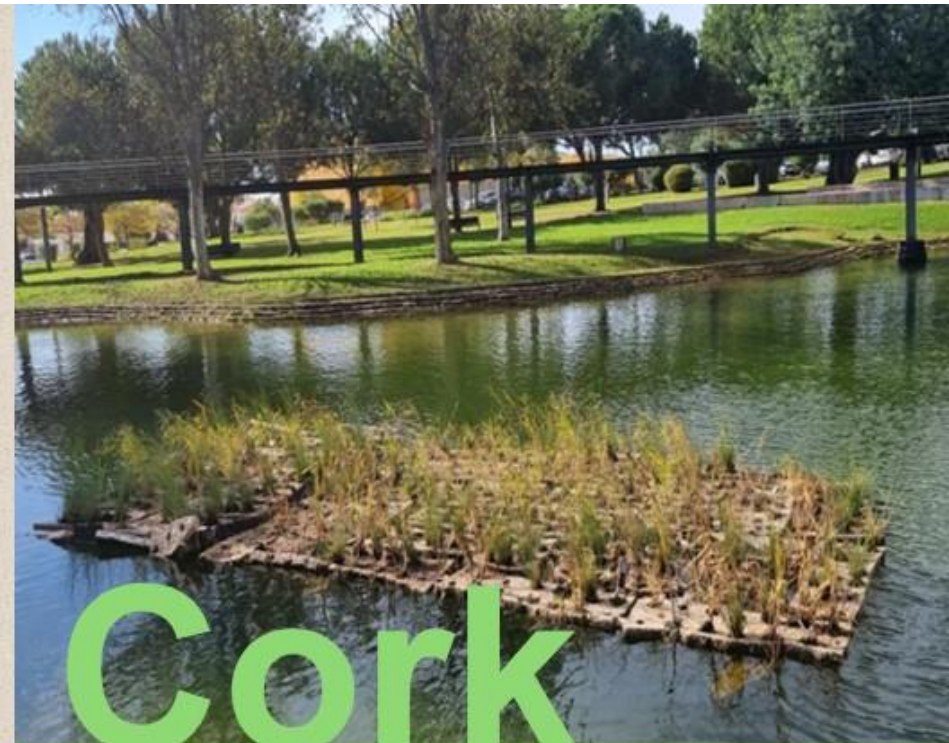
The first implementation of this biodevice took place in the small urban lake located in Jardim das Comunidades, Almancil. The lake had been experiencing significant eutrophication problems, characterized by excessive algae growth and deteriorating water quality. The introduction of the biodevice has led to a noticeable improvement in water clarity and a reduction in some nutrient levels. The project has demonstrated the effectiveness and feasibility of this innovative approach in urban water management.

Further information, including building instructions, can be requested from the project coordinator at UAIG:
Prof. Dr. Manuela Moreira da Silva; msanti@ualg.pt

This project was a collaborative effort by Instituto Superior de Engenharia of the UAIG and the Municipality of Loulé.



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Design: Prof. Dr. Manuela Moreira da Silva & Leon Kanigowski



Cork EcoWetland

Macrophyte Vegetation in Natural Cork

Cork EcoWetland

This biodevice is made of locally sourced cork, which serves as a support for native macrophytes of the genera *Typha*, *Phragmites*, and *Juncus*, with the ability to prevent water eutrophication by removing nutrients (mainly nitrogen and phosphorus), without the need for energy consumption, promoting biodiversity for example by serving as a habitat for fish and aquatic birds.



- ✓ **Sustainable**
Local cork
Native plants
- ✓ **Modular**
Adaptable to different needs
- ✓ **Water quality Improves**
- ✓ **Cork**
Low density = good buoyancy

- ✓ **Maintenance Cost**
Low
- ✓ **Rebuildable**
In-house; only materials need purchasing

Functions	Removal of nutrients (nitrogen and phosphorus) dissolved in water	Reduction of organic load and therefore lower risk of eutrophication
	Oxygenation of the water column	
	Removal of potential urban pollutants, e.g., phytoremediation of heavy metals	
Other Eco-services	Act as habitats for native bird species, improving urban biodiversity	
	Promote atmospheric carbon sequestration by chlorophyll-containing aerial organs (leaves and stems)	
	Their roots enhance aquatic biodiversity (zooplankton and fish fauna)	
	Create shading in the water column and consequently reduce its heating	



- Cork cubes as spacers between boards avoid overlapping
- Approx. 40 cm long rope pieces connect the cork pieces & are threaded through the spacer cubes



- Conical holes; size & shape adapted to macrophytes (e.g. square)

- Thicker rope on one or several sides connects to shore or anchor

História de Sucesso:

Jardim das Comunidades, Almancil

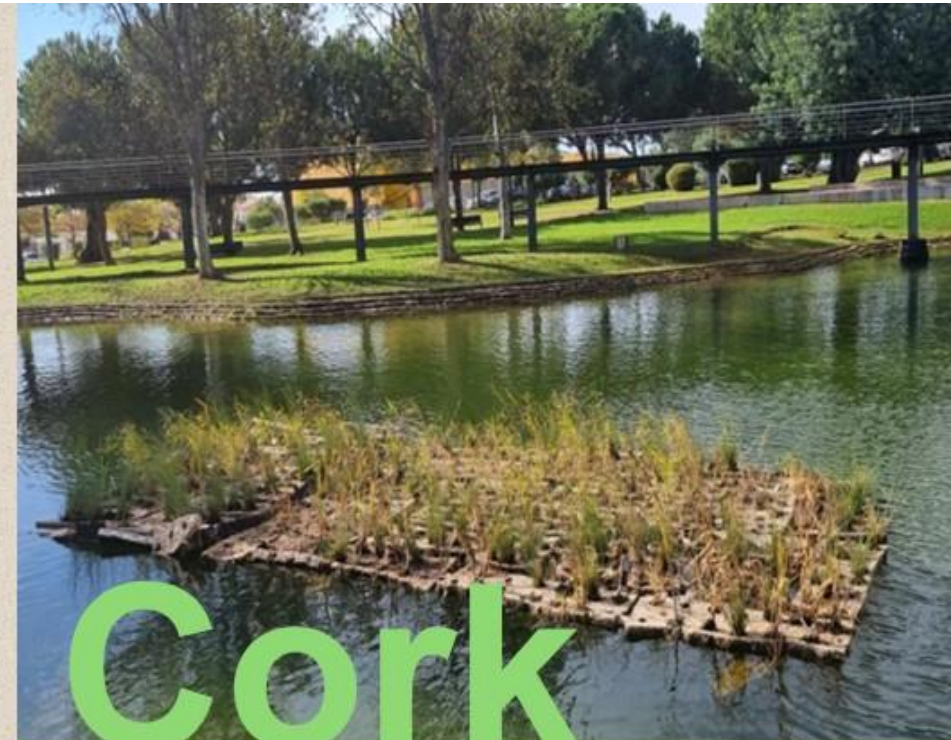
A primeira implementação deste biodispositivo teve lugar num pequeno lago urbano localizado no Jardim das Comunidades, Almancil. O lago havia experienciado problemas significativos de eutrofização, devido ao crescimento excessivo de algas e deterioração da qualidade da água. A introdução do biodispositivo levou a um aumento notável da clareza da água e redução dos níveis de nutrientes. O projeto demonstrou a eficácia e a viabilidade da sua abordagem inovadora na gestão de água urbana.

Mais informações, incluindo instruções para a construção do mesmo, podem ser solicitadas à coordenadora do projecto na UAlg:
Prof. Dr. Manuela Moreira da Silva; msanti@ualg.pt

This project was a collaborative effort by Instituto Superior de Engenharia of the UAlg and the Municipality of Loulé.



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Cork EcoWetland

Vegetação Macrófita em Cortiça Natural

Cork EcoWetland

Este biodispositivo é feito de cortiça de oringel local, que serve de suporte a macrófitas autóctones dos géneros Typha, Phragmites e Juncus, com a capacidade de prevenir a eutrofização da água removendo nutrientes (principalmente azoto e fósforo), sem a necessidade de consumo de energia, promovendo a biodeversidade ao servir de habitat para peixes e pássaros aquáticos.



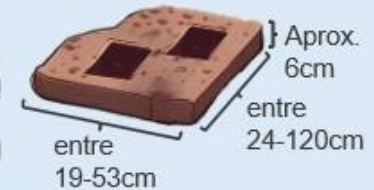
- ✓ **Sustentável**
Cortiça local
Plantas autóctones
- ✓ **Modular**
Adaptável a diferentes necessidades
- ✓ **Qualidade da água**
Melhoria
- ✓ **Cortiça**
Baixa densidade
Boa flutuabilidade

- ✓ **Manutenção**
Baixo custo
- ✓ **Reconstrução**
Interna; é apenas necessário adquirir os materiais

Funcionalidades	Remoção de nutrientes (azoto e fósforo) dissolvidos na água	Diminuição da carga orgânica e do risco de eutrofização
	Oxigenação da coluna de água	
Outros Eco-serviços	Remoção de eventuais poluentes urbanos ex. fitorremediação de metais pesados	
	Funcionam como habitats para a avifauna autóctone, melhoria da biodiversidade urbana	
	Promovem o sequestro de carbono atmosférico pelos órgãos aéreos clorofilinos (folhas e caules)	
	As suas raízes promovem a biodiversidade aquática (zooplâncton e ictiofauna)	
	Criam sombreamento na coluna de água e conseqüente atenuam o seu aquecimento	



- Cubos de cortiça usados como espaçadores para evitar sobreposição das mesmas
- Aprox. 40 cm de corda ligando as diferentes peças de cortiça, enfiadas nos cubos espaçadores



- Orifícios cónicos; tamanho e forma adaptados às macrófitas (ex. , quadrado)

- Corda mais resistente num ou mais lados para ligar à margem ou à âncora

Compared to comparable leaflets/flyers/brochures it can for instance be said that Alhárabe (2021) does not provide an exact description of the design, probably to “conceal” its simplicity and therefore make it less likely potential customers produce it themselves. But it does have a wide selection of plants that they offer which wasn’t necessary for our case in Almancil because we have chosen the plants for the reasons described in chapter 3.3.3 and mainly focus on eutrophication problems in the Algarve with this biodevice.

4.5 DISCUSSION

To assess rather the ROs described in chapter 1.1 have been met it is important to take a critical look at the results of the previous subchapters, to illustrate connections and to examine the effectiveness of the biodevice.

Comparison between the values from 2019/2020 by Pimenta (2021) with the values obtained as part of this study is mostly impossible due to differences in the survey methods and seasonal differences. Comparing the results for dissolved oxygen saturation shows that this value improved after the implementation of a biodevice in both cases (meaning 2019/2020 and 2022/2023). Between 2022 and 2023 the levels of ammonium decreased. A study by Qiao & Ma (2022) found that dissolved oxygen considerably increased while ammonium and TP decreased (72.03% and 63.16% removal rates, respectively) after the implementation of CFWs.

The nutrient dynamics described in chapter 4.1 indicate that the chlorophyll *a* concentration measured in 2023 remained low despite the spike in total nitrogen and the slightly increased total phosphorus values. This is also represented by the TSI (Chl-*a*) value staying within the mesotrophic range while TSI (TP) passed from oligo-mesotrophic to slightly eutrophic and TSI (TN) from moderately eutrophic to hypereutrophic. Hartshorn *et al.* (2016) attest CFWs a positive influence on Chl-*a* values by remediating N and P. The stabilisation of the Chl-*a* value is a direct indicator for having controlled algae proliferation (Park *et al.*, 2015). Since the Chl-*a* values only increase slightly while having high TN values and only slightly increased TP values, it seems as if TP could be seen as the limiting factor for Chl-*a* (Bennett *et al.*, 2021; Hartshorn *et al.*, 2016; Park *et al.*, 2015).

Low amounts of algae are also important for the visual perception of the lake by the park visitors (Flanzenbaum *et al.*, 2022). A study about some urban lakes, including the Central Park in New York City which also seems to be supplied with tap water, describes the risk of high nutrient levels potentially leading to cyanobacteria and the negative effects of algae on

the appearance (Flanzenbaum *et al.*, 2022). A study by Zhang *et al.* (2019) observed very positive effects of bioremediation by aquatic macrophytes on urban park water bodies water quality. According to Bi *et al.* (2019) CFWs “increase the recreational value by improved aesthetics”.

The reasons for the strong TN increase between 2022 and 2023 despite the installation of the biodevice cannot be explained with certainty without conducting further research. There is however a high chance that the observed population increase of the not yet further defined turtles and fish in the lake play an essential role in the exploration of the TN value in 2023. Chapter 4.1.2 describes the possible negative impact of the animals on the aquatic nutrient cycle in the lake, mostly due to excretion, faeces and decomposition which are well researched influences (Chen *et al.*, 2013; Halvorson & Atkinson, 2019; Kajimura *et al.*, 2004; Lee *et al.*, 2006; Nędzarek *et al.*, 2015; Song *et al.*, 2015; Sterrett *et al.*, 2015; Thayer *et al.*, 1982; Yavuzcan Yildiz *et al.*, 2017). Research about the effluent of commercial turtle farms state that it can cause serious water pollution due to its high nutrient load (Xiang *et al.*, 2013). Especially turtles also have the ability to ingest big amounts of plant material (Chen *et al.*, 2013; Ip *et al.*, 2012; Lee *et al.*, 2006; Song *et al.*, 2015; Thayer *et al.*, 1982) which might have negative effects on the macrophytes used in the biodevice if the turtles also eat parts of the macrophytes used in the biodevice. In a study by Wang *et al.* (2015) about CFWs the roots of the vegetation were protected with a plastic fence to avoid disturbance by waterfowl and turtles. This precaution underlines the reasonability of the assumption that turtles might feed on plant parts.

As far as the biodevice is concerned, the values mean that algae growth seems to have been well contained (Chl-a values). Almost all of the substances freely available to plants, being nitrates, nitrites, ammonium and orthophosphates, are extremely low, which suggests that the macrophytes absorb these substances as described in chapter 3.3.3 and that the algae therefore have no supply of nutrients. It seems as if the macrophytes in the biodevice behaved as expected by taking up plant available N and P forms. Two reviews about field based CFW studies clearly support this hypothesis (Bi *et al.*, 2019; Lucke *et al.*, 2019). It is highly likely that the eutrophic state of the lake would be worse without the nutrient sequestration effect of the biodevice. Given the low amounts of inorganic nitrogen and orthophosphates there is no indication for the necessity to install more square meters of biodevice at this point. It is important however to make sure that maintenance is undertaken (e.g. cutting the plants and removing the cut off plant parts) to ensure that the nutrients taken up in the plant tissues are being removed from the local nutrient cycle. The necessity of permanently removing biomass

from CFWs through cutting/harvesting is widely recognized (e.g. Huth *et al.*, 2021; Lesutienė *et al.*, 2024) though the exact way how to undertake such actions depends on the circumstances. Ayres *et al.* (2022) for example state: “*While the frequency and suitability of harvesting is subject to climate and plant species selection, it is an effective means of permanently removing nutrient loads that could otherwise impair water quality*”.

To support the remediation of the total nitrogen through the macrophytes it could be an idea to assess how to support the ammonification process to support the processes of the aquatic nutrient cycle (Sun *et al.*, 2024). A suggestion worth taking into consideration could be to introduce or support bacteria with high ammonification rates, for example *Bacillus amyloliquefaciens* (Hui *et al.*, 2019). Assessing if there might be an angle using bacteria to help transform the organic N of the total N into ammonium which the macrophytes can phytoextract could be interesting for future research. A study from Poland introduced effective microorganisms to a shallow lake suffering from eutrophication with positive results regarding increased ammonium concentrations (Dondajewska *et al.*, 2019).

Another measure could be to remove the aquatic animals from the lake, similar to what was undertaken in 2021, and monitor the effect on water quality.

It is likely though not observed that park visitors feed the aquatic animals which would add nutrients to the cycle. While this has not been observed ‘in flagranti’ during any of the field visits, common sense suggest it happens and literature supports the hypothesis (Turner & Ruhl, 2007).

The structure of most of the biodevice designs has proven to be stable so far which is important taking into consideration that the previous CFW made out of agglomerated cork quickly became unusable due to problems with the material. Design 2 however should be reconsidered or at least altered to avoid that the soaked wood beams pull the plant holding cork pieces under the water. Changing design 2 into a version without wooden beams should be relatively easy since the wood can be taken out and the plant holding cork pieces reconnected with the rope they already have. This action would have to be undertaken in the water to avoid ruptures.

Design 3, since it seems more robust, could be an option for rivers or lakes with rougher conditions than the Almancil lake. Design 1 and 4 were aesthetically most pleasing, used less different materials and proofed to be stable under the relatively calm conditions (e.g. no strong current) in the Almancil lake.

A rope made from natural materials would make the biodevice 100% ecological. Wool rope could be an innovative option though it needs further testing and research, especially regarding

its tensile strength (Drury & Crotty, 2022). Wool has a long history in Portugal (Pastor *et al.*, 2021) and innovative uses could be interesting to support the struggling wool industry (J. Rodrigues *et al.*, 2002).

As described in chapter 3.2 the study design had some limitations from the beginning which were unavoidable due to the combination of requirements that the combination of RO brought along. The unexpected presence of the aquatic animals and the not clearly explainable change in parameters clearly underlines those limitations. To clearly assess the potential effectiveness of the biodevice lab studies would have to be undertaken, even though Bi *et al.* (2019) state that laboratory studies of CFWs often suggest better pollutant removal performance than those observed *in-situ*.

The methodological error in the assessment of the transparency value is unfortunate, especially since it could have given another TSI value and indication towards the functionality of the biodevice. In order to correct the error in the transparency methodology afterwards, it would have been possible to use a satellite remote sensing method, but this would have gone beyond the scope of the work (Gomes *et al.*, 2020). The Chl-a value is related to water clarity. High Chl-a values often mean lower water clarity because of higher algae contents which reduce light penetration (Mamun *et al.*, 2019; Yip *et al.*, 2015). Together with the observation that the visibility was good the error could be seen as a bit less substantial.

The developed flyer stands out for its ability to summarize the findings of the study onto two A4 pages in a non-scientific language which makes it a good tool to present the idea to other decision makers along the Algarve. It embraces the idea of in-house solutions rather than buying commercial solutions which is most likely to be more economical. In the future it could even be an idea to create biodevices together with city dwellers in form of workshops or action days. The involvement of citizens would reduce costs and promote closeness to nature and a sense of responsibility.

All in all, the results show that the biodevice stabilised or improved most of the assessed values and prevented algae bloom. All forms of inorganic nitrogen and orthophosphate remained under control despite the massive rise in the presence of aquatic animals. Further research is needed to better observe and explain the spike in total nitrogen. Three out of four tested designs have proven themselves so far, with design 1 and 4 being the preferred options for using less different materials and aesthetics. All ROs described in chapter 1.1 have been met with a restriction in relation to the values of total nitrogen and total phosphorus.

5

FINAL CONSIDERATIONS AND FUTURE RESEARCH

The dissertation showed the possibility of creating a viable CFW design in-house without the need for commercial solutions. The developed biodevice seems like a good contribution to the toolbox of NbS, considering that it involves natural local resources, autochthonous vegetation and phytoremediation processes known for improving water quality. So far structural stability of most of the biodevice designs could be observed. The water quality parameters for freely available inorganic nutrients, orthophosphates and Chl-a remained stable on a low level which is likely to relate to the presence of the macrophytes of the biodevice. An extreme increase in total nitrogen could be observed which can be related to the reintroduction in the lake of exotic fish and turtles.

The biodevice can be replicated without the need of highly specialised personnel or expensive machinery since the manual tasks for its recreation are basic (see “construction manual” in chapter 3.4). This enhances the feasibility for municipalities in the Algarve to replicate the biodevice in its exact form using cork. The idea was to use local materials so this design using cork should only be used in regions where cork is planted. Due to the simplicity of the building process, the new biodevice could also be interesting for other situations in which water bodies face eutrophication. The idea of using a natural material as buoyant material can be transferred to other regions with different materials locally available to help mitigate anthropogenic pressure on water bodies. The principle could therefore also be interesting for development cooperation contexts that aim at fulfilling SDG 6. In this study, only minimal unnatural materials were used for the prototype, and they can be avoided once a suitable natural rope is tested.

As mentioned in chapter 3.1.3, a large number of exotic specimens were already removed in 2021, to contribute to improving water quality and the repetition of such a removal action is recommended. Alongside these measures, it is essential to improve communication with the community in order to eradicate the practice of dumping these animals in the lake. It is proposed to create an alternative way, which guarantees the necessary conditions for animal welfare without destroying the ecological balance of urban ecosystems, for people to give up their animals when no longer wanted. Furthermore, there might be a need to inform Almancil's population about the risks of exotic species being released into the lake and to avoid anyone feeding aquatic animals. Simple measures like informational boards and a website could be an effective first response to the problem. More options could include newspapers and teaching children in school about the problem¹⁵.

Deploying CFWs and reducing the density of aquatic fauna (and avoiding exotic species) seem to be viable measures to improve the water quality of urban lakes in other parts of the world too. An example from the north of Europe shows that the city of Berlin included similar efforts to improve the water quality of a park lake which suffered from eutrophication. Fish were removed through electrofishing and CFWs deployed (Bezirksamt Mitte, 2022; Luisenstadt Mitte, n.d.). Electrofishing could be a viable option for the Almancil lake too to avoid wasting water by lowering the water level to use nets like in 2021. On the other hand, electrofishing does not seem to help to remove turtles (Bezirksamt Mitte, 2022).

While research objectives two (test biodevice) and three (create a flyer for dissemination) have been fully met, objective one (develop a prototype for phytoremediation of nutrients from urban water bodies to improve its ecological status [...]) has only been fulfilled partly since the overall improvement of TSI(s) was not clear. The exact reasons cannot fully be evaluated though the findings of the study and complementary literature about CFWs suggests that external factors must have played a key role.

¹⁵ An example of such measures from Berlin, Germany can be found here: <https://www.berlin.de/ba-mitte/politik-und-verwaltung/aemter/umwelt-und-naturschutzamt/naturschutz/artikel.1096510.php> (last accessed 20.01.2025). The measures were undertaken to combat very similar problems to the ones in Almancil.

The open nature of the Almancil lake led to great variability of the data, which makes it difficult to completely isolate the effects of the biodevice from other influences. The disadvantage of the study design was known but had to be accepted in order to react to the imminent deterioration in water quality. To decrease these evaluation challenges, a more comprehensive study would be needed, with a larger sample size and continuous monitoring. According to head of the project at the ISE-UAAlg, the next step is to equip the biodevice with sensors to continuously monitor water quality parameters. The obtained data would be a great base for further studies and more detailed assessments of the performance of the biodevice. Controlled laboratory experiments could also help to better understand the specific contributions of the biodevice in different conditions and environments.

From today's point of view, the biodevice seems like a first good version of a CFW. Literature suggests that the chosen species are good at phytoremediation and the results show that all the directly available forms of P and N were indeed controlled despite a steep increase in total N. The most innovative part of the biodevice was the structure of the buoyant body devised as part of this study. Most of the tested structure designs showed stability so far though long-term observation is necessary to be able to give an indication on how long the biodevice is usable. At this point, the only change which clearly needs to be made is removing the wooden beams from design 2. Maintenance, especially pruning the macrophytes, has to be undertaken after the development of a maintenance plan which was not part of this dissertation due to its natural limitations in scope. For future projects, it would be interesting to find a natural rope to connect the corkboards.

For future research, there are different ideas worth taking into consideration. They could be a good subject for further scientific studies, including:

- A more detailed monitoring of water quality and macrophyte growth in biodevices;
- Studies focused on phytoremediation processes, not only of nutrients but also of potential urban pollutants;
- Monitoring of the sediment's status;
- Biodevice sensing for automation of water circulation in the lake;
- Test eventual nutrient release of the cork by degradation into the water and the reaction of aquatic animals;
- Providing scientific monitoring of biodevice maintenance and the resulting experience;

- Calculate the maximum tensile strength when pulling the rope connections between the cork boards, especially with wet cork boards, to assess if suitable for rough conditions;
- Assessment of the characteristics of the cork after several years in wet conditions;
- Scientific assessment of the biodiversity arising from the biodevice;
- A cost analysis of the biodevice taking materials and work time into consideration;
- Long term observation of the floating structure, especially its buoyancy.

In conclusion, it can be stated that this project showcases the potential of this Nature-based solution which can offer contributions to urban water quality management and at the same time be adaptable to sustainability at a local level. The biodevice has so far proven its stability and the algae population has been controlled despite high levels of total nitrogen which are suspected to be attributable to the introduced exotic animals. The flyer and detailed building instructions provided in this work allow other entities interested in the biodevice to reproduce it in-house. Furthermore, it conveys the concept of using green solutions to tackle challenges connected with urban water management which are going to become more severe looking at growing cities and climate change. The biodevice developed in this study could be seen as a small contribution to achieving SDG 6 mentioned in the introduction.

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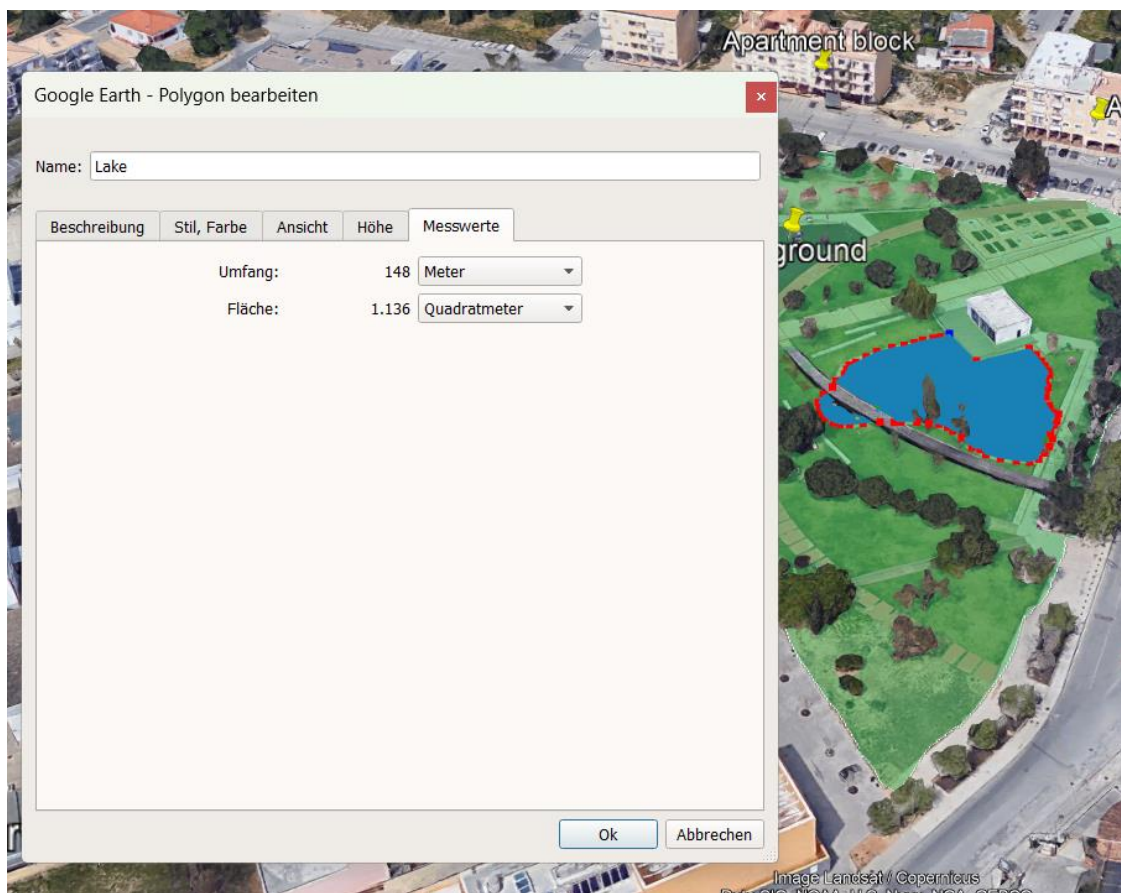
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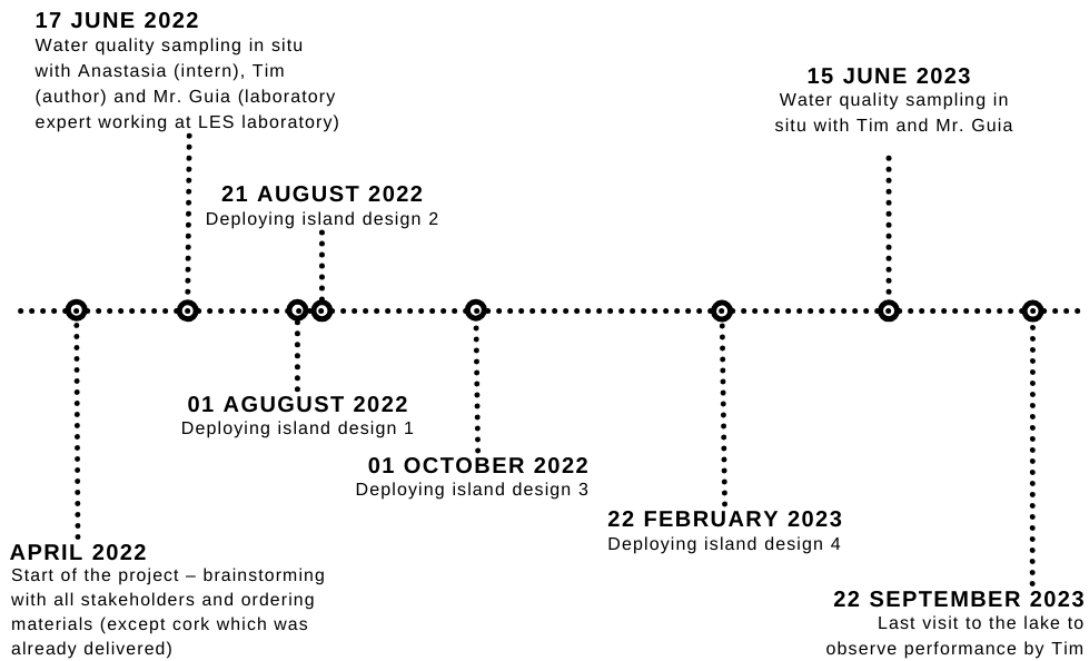
A

APPENDICES

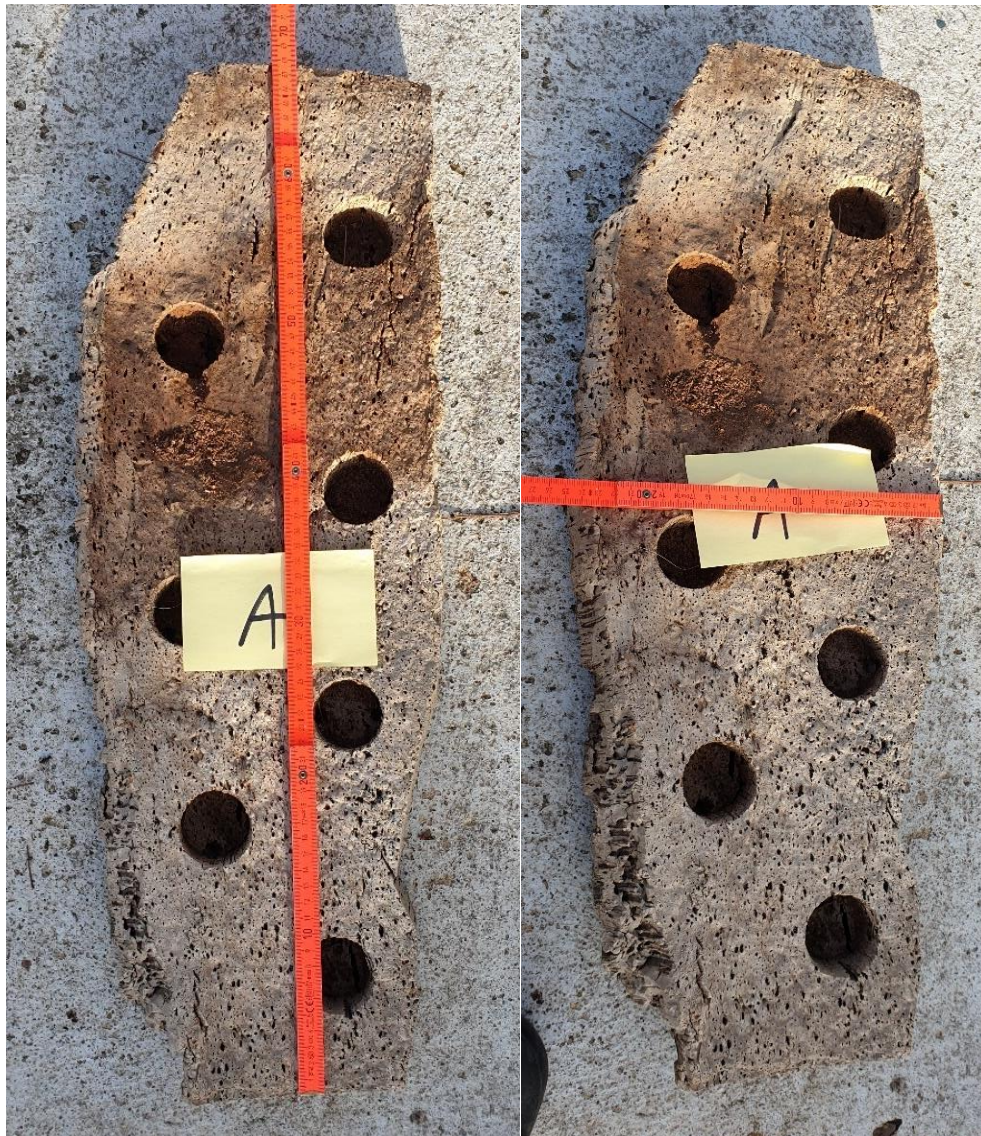
Appendix A – GoogleEarth Pro lake polygon properties



Appendix B – Timeline of the project



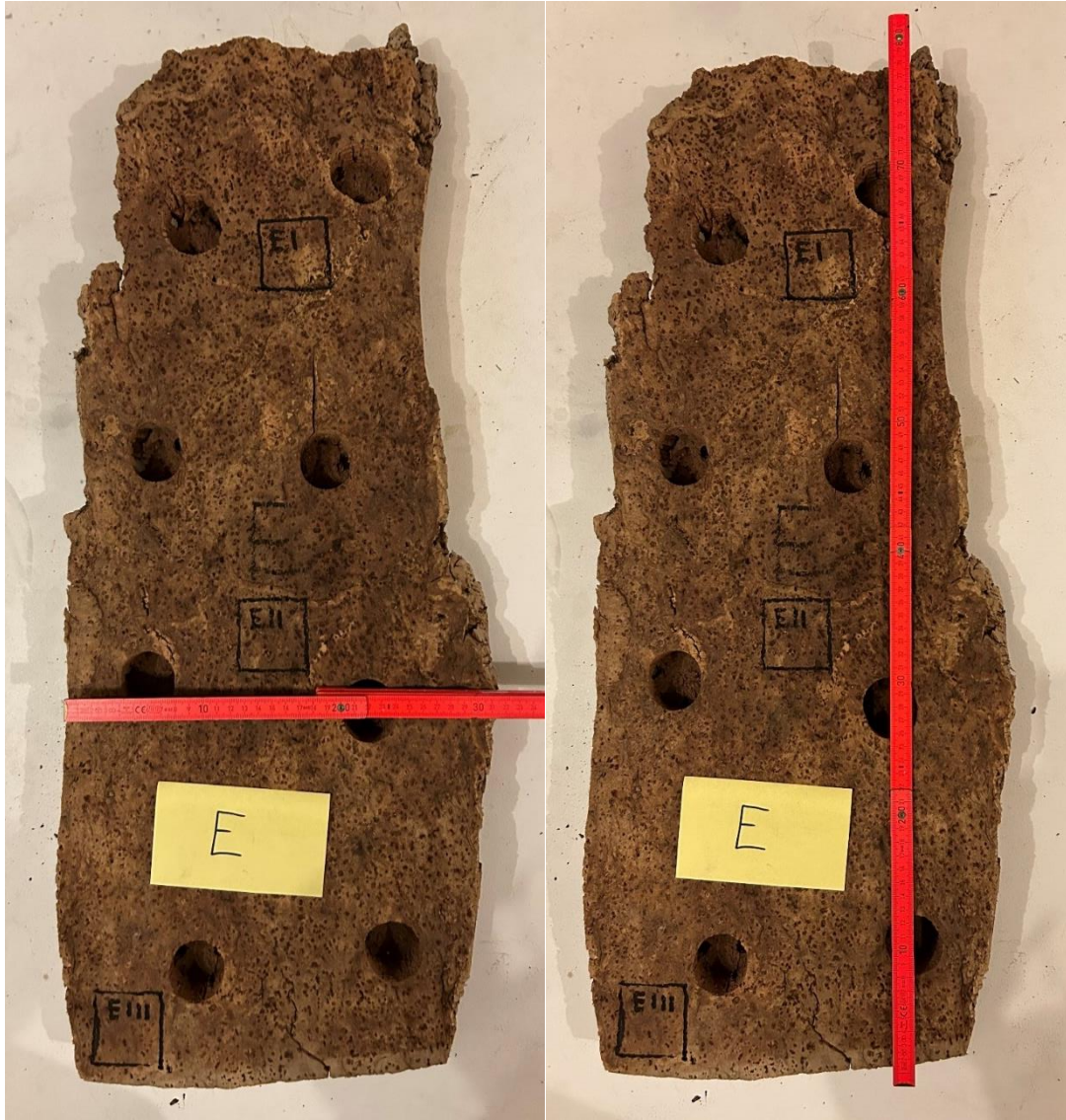
Appendix C – Pictures of 10 cork boards 30 sample cubes were taken from

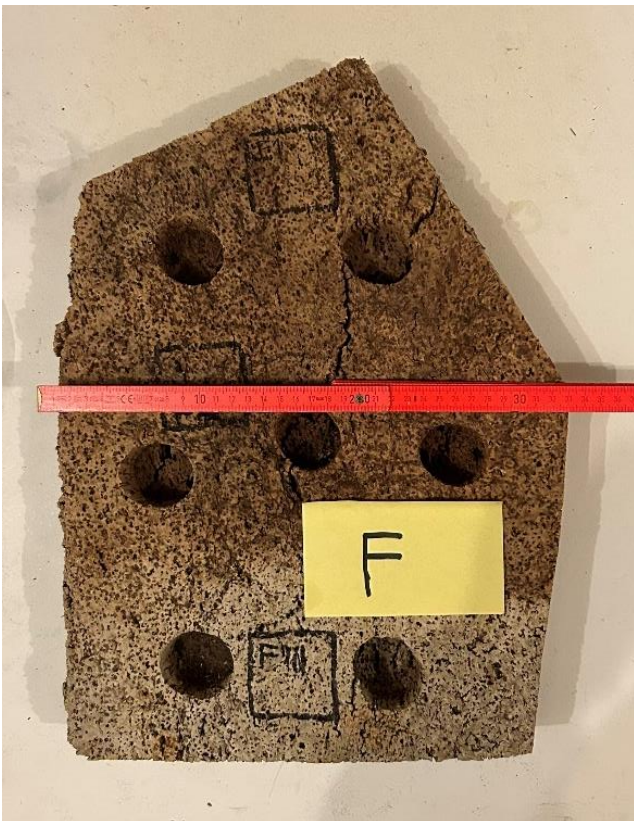
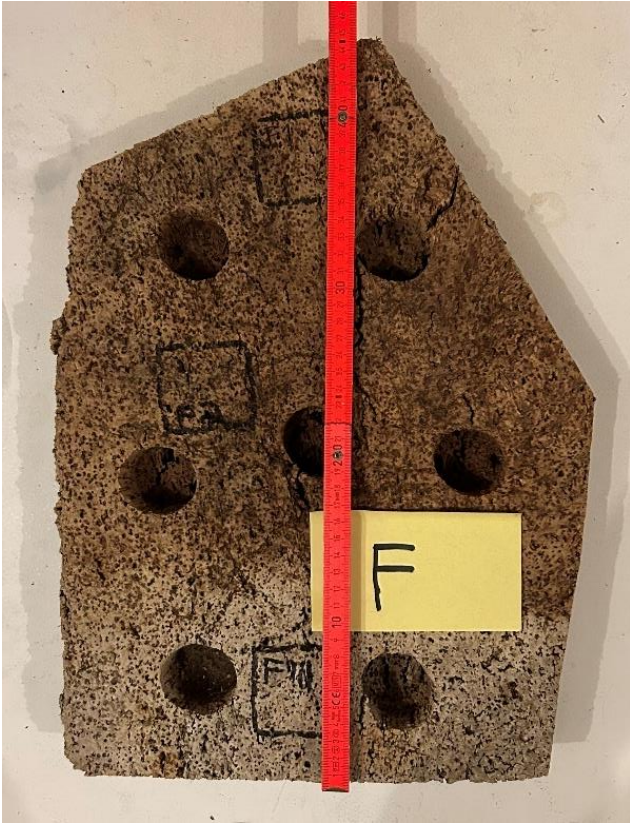


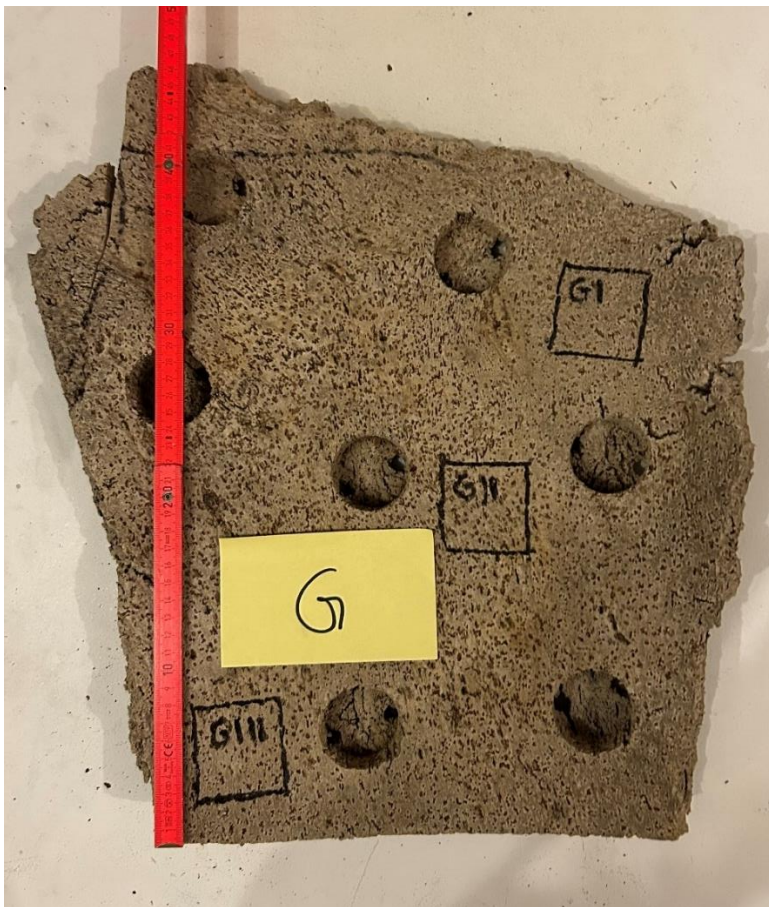
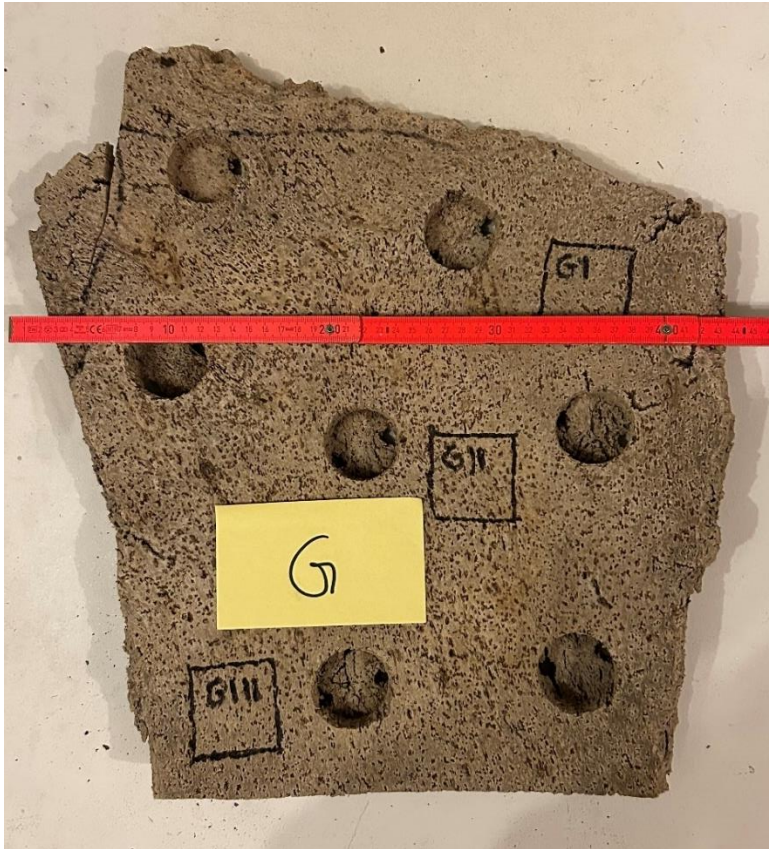




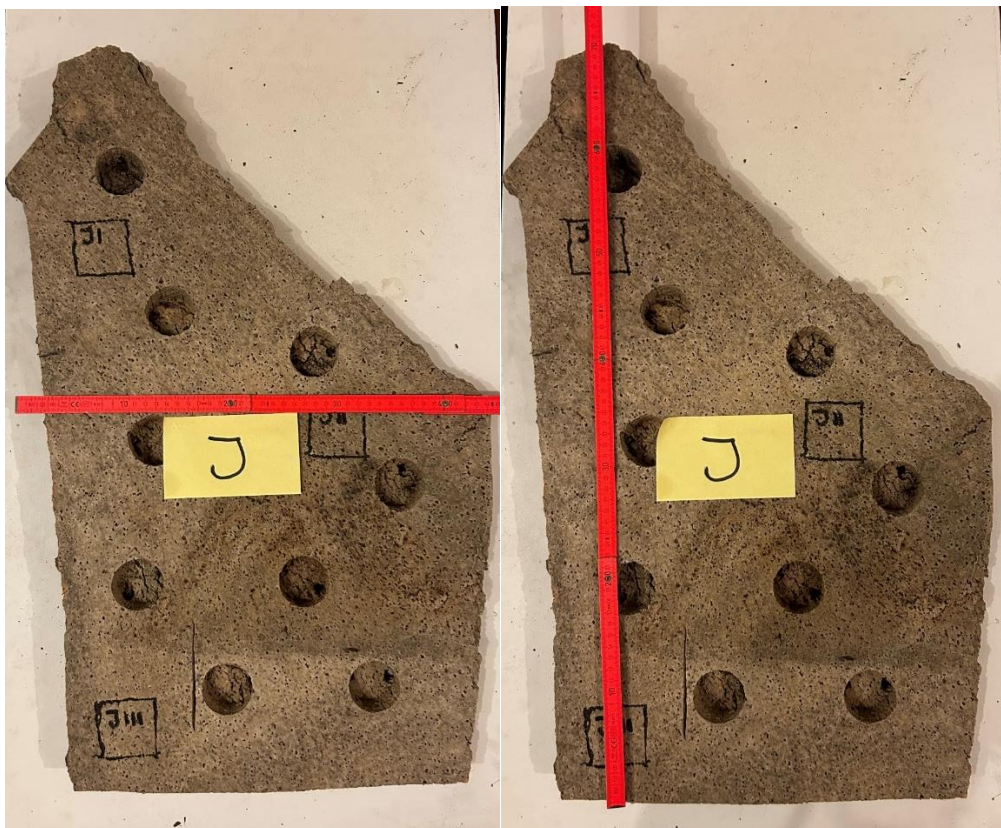
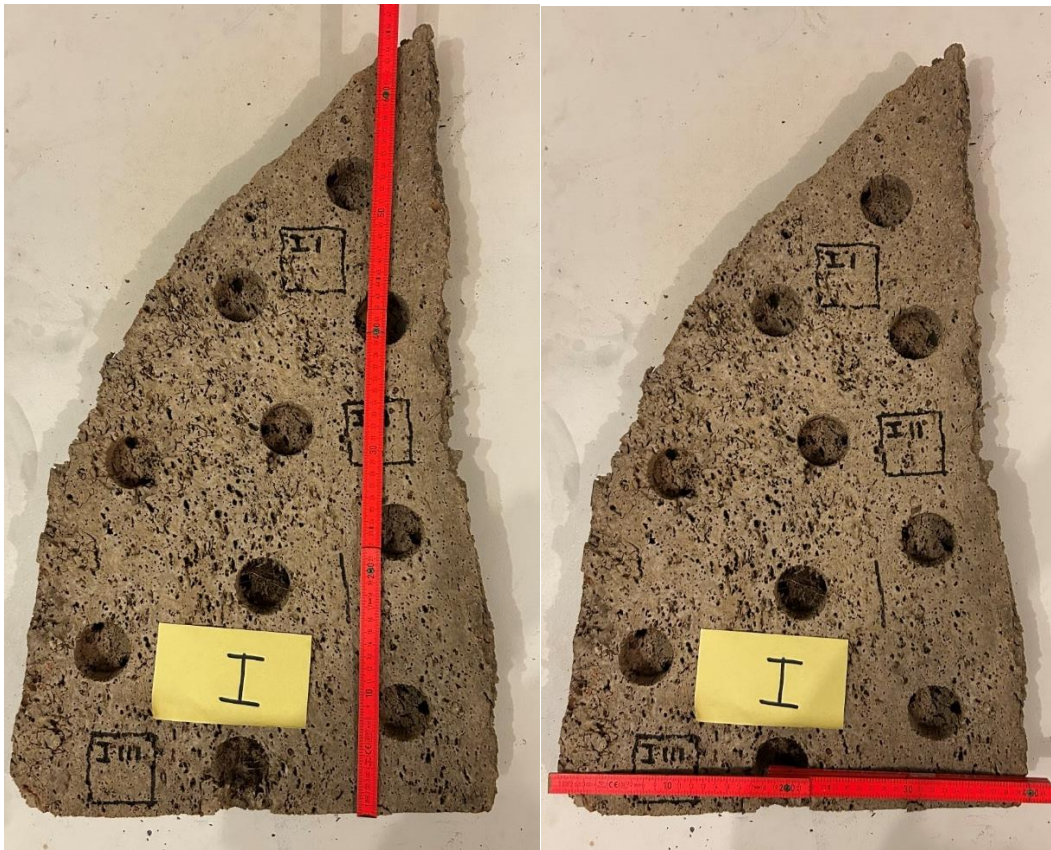












Appendix D – Density assessment test set-up

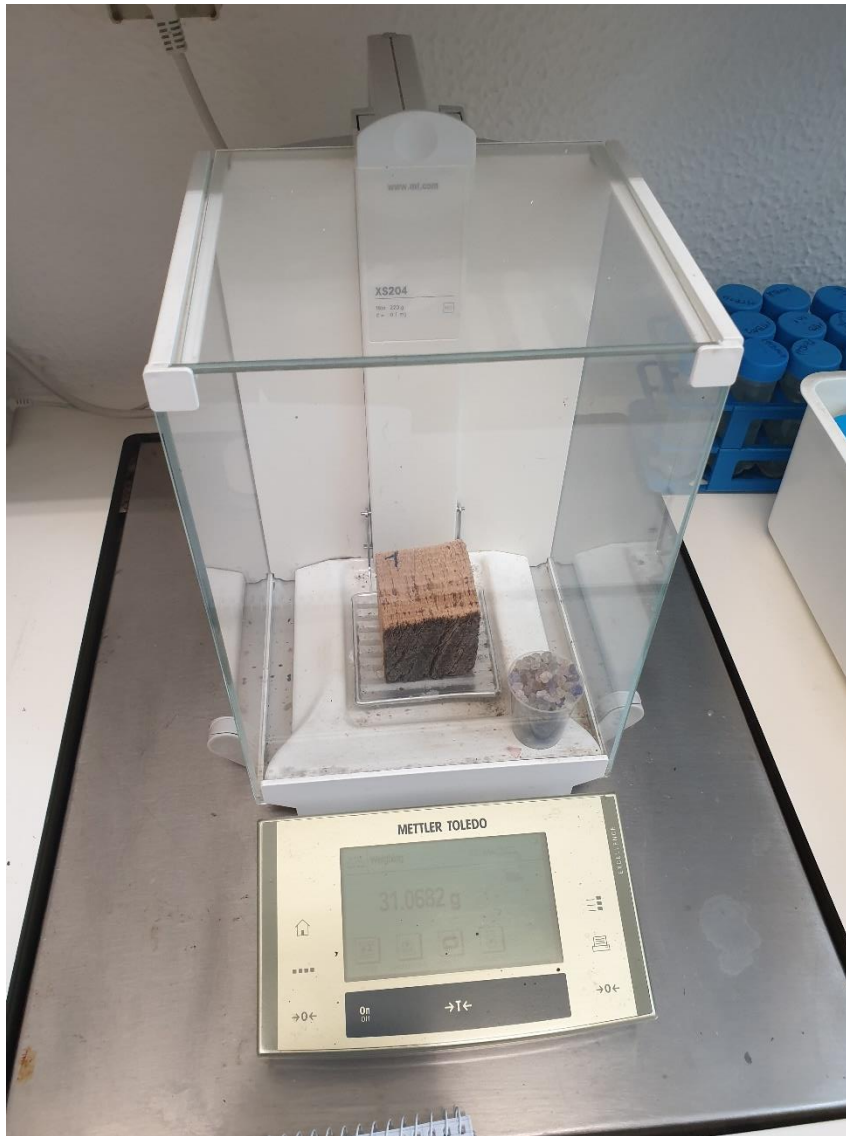
After cutting out the cork pieces they were dried...



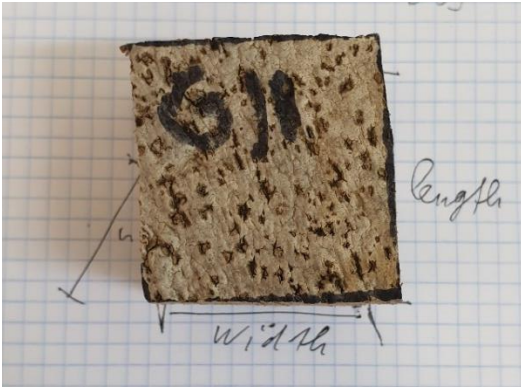
...and stored in desiccators to avoid humidification of the samples.



A laboratory scale was used to assess the weight of the samples.



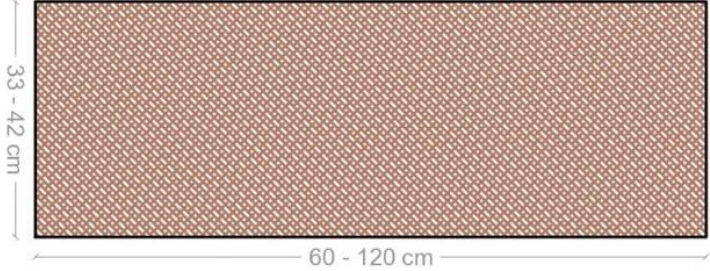
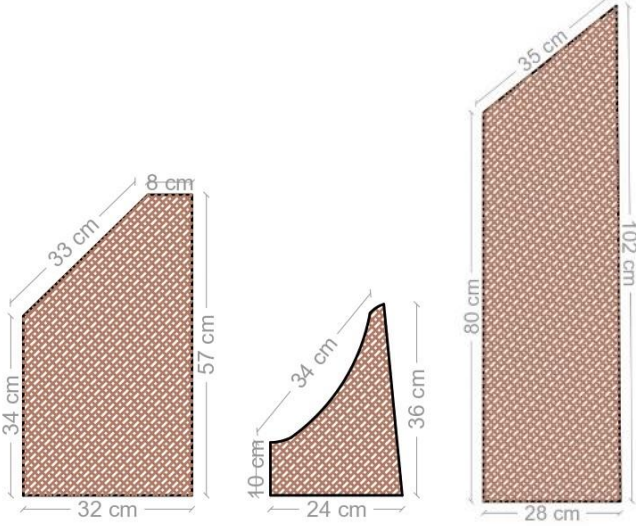
The measures of the samples were taken after defining which way to measure height, width and length.



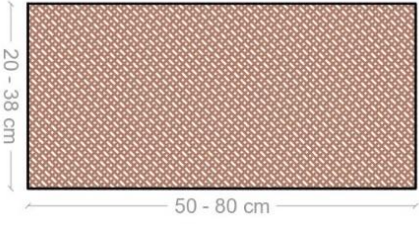
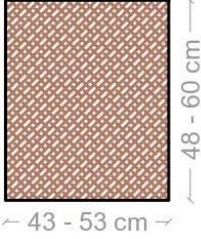
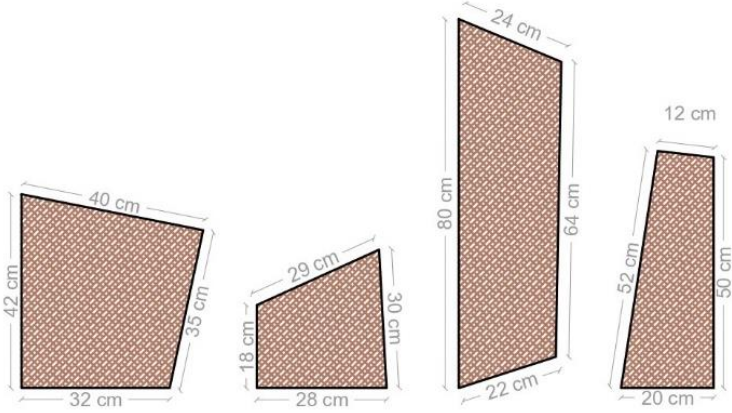
Finally, the second way to measure the volume of the cubes was carried out.

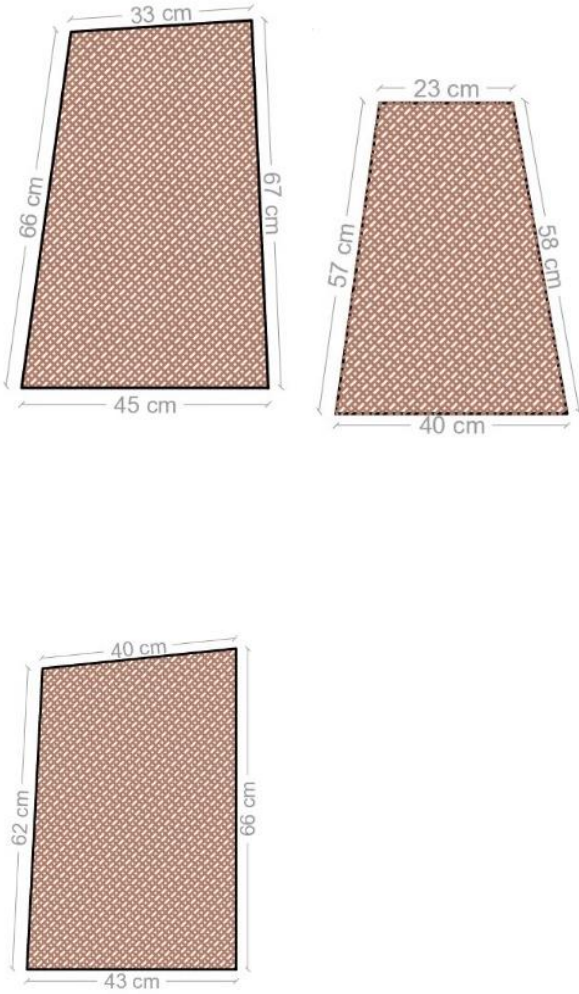


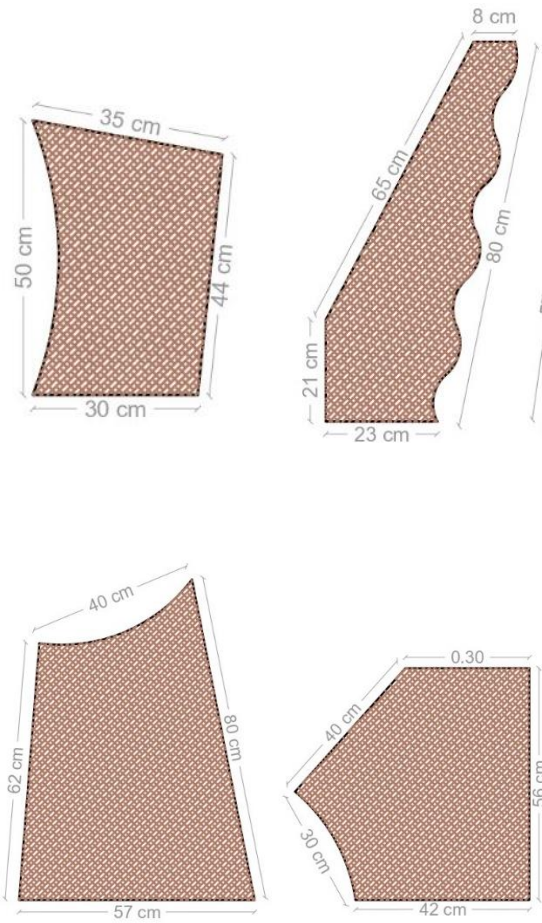
Appendix E – Description of cork boards that were delivered for the project

Category Nr.	Shape description	Amount of boards (Total of boards that were on 5 pallets = 867)	Schematic shape representations (based on examples taken from category)
I	Big rectangles	31	
II	Irregular quadrilaterals	130	

III	Small rectangles	114	
IV	Very small rectangles	52	
V	Small almost squares	57	

VI	Medium sized rectangles	138	
VII	Bigger almost squares	27	
VIII	Trapezoidal shapes	144	

			
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IX	Irregular shapes	174	
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Appendix F – Image of *in-situ* “test-setup” to estimate load capacity of soaked cork



Picture taken and test performed on 22.09.2023 by author