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MAIN IMPACTS OF WASTEWATER REUSE FOR GOLF COURSES IRRIGATION

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Thesis Supervisors:
Professor Manuela Moreira da Silva (ISE/UAlg)
Professor Carlos Guerrero (FCT/UAlg)

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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I hereby declare to be the author of this work, which is original and unpublished.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.

SEGUN EMMANUEL GEORGE

Glory be the father
&
Almighty

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RESUMO

O golfe é uma atividade crucial para o turismo no Algarve, pelo que apostar no seu desenvolvimento sustentável é da maior relevância para a socioeconomia da região e do país. Perante o cenário de escassez de água no Mediterrâneo, incluindo o Algarve, tem-se investido crescentemente na reutilização de água para a rega de campos de golfe. Esta dissertação é uma primeira abordagem para se avaliar as implicações ambientais e económicas da reutilização de águas residuais tratadas (ApR) para rega de campos de golfe no Algarve. Foram analisados quatro campos de golfe, Salgados, San Lorenzo, Castro Marim e Quinta do Vale, e as três ETAR que os podem abastecer com ApR, as de Albufeira Poente, Quinta do Lago, Vila Real de Sto. António. Quantificou-se as necessidades de rega dos campos de golfe, a disponibilidade de ApR, os nutrientes (N e P) fornecidos pela ApR e a respetiva redução no uso de fertilizantes de síntese, as emissões de carbono associadas à rega com água de origem natural/ApR e as diferenças de custos relacionadas com a introdução da ApR na rega.

Embora preliminares, os resultados indicam que em termosde disponibilidade a ApR demonstra um forte potencial de utilização para rega dos campos de golfe, poderia satisfazer totalmente a procura de água no Salgados, e nos outros campos pode suprir entre 40 a 90% das necessidades. Para além de reduzir o consumo de água de origem natural, o uso de ApR reduz a necessidade de fertilizantes de síntese azotados entre 10 a 70 % e pode substituir totalmente os fertilizantes fosfatados, evitando assim nos quatro campos estudados a emissão de 14,5 t CO_2e por ano. Em termos económicos, o uso de ApR nos campos Castro Marim e Quinta do Vale representa redução de custos, já em San Lorenzo e Salgados a atualização dos preços da ApR podem aumentar os encargos associados à rega, mas significam maior segurança no seu uso, em conformidade com os requisitos da UE para reutilização de água residual tratada.Assim, embora este estudo careça de ser aprofundado para integrar outros aspetos como por exemplo, uso de novas ferramentas eletrónicas (incluindo, IoT e IA) para otimização da gestão da água, energia, solos, relvas e fertilizantes, constata-se que o uso de ApR na rega de campos de golfe no Algarve permite melhorar a sutentabilidade ambiental do setor. Foi por exemplo, demonstrado que a redução da pegada carbónica por volta de golfe no Algarve pode atingir os 198 g CO_2e.

Palavras-chave: ApR, sustentabilidade, emissões de carbono, escassez de água, reciclagem de nutrientes.

ABSTRACT

Golf is a crucial activity for tourism in the Algarve, making investment in its sustainable development highly relevant to the socioeconomy of the region and the country. Given the scenario of water scarcity in the Mediterranean, including the Algarve, there has been increasing investment in water reuse for irrigating golf courses. This dissertation is a preliminary approach to assess the environmental and economic implications of using treated wastewater ((“Água para Reutilização”, ApR) for irrigating golf courses in the Algarve. Four golf courses were analyzed—Salgados, San Lorenzo, Castro Marim, and Quinta do Vale—as well as the three wastewater treatment plants (WWTPs) that could supply them with APR: Albufeira Poente, Quinta do Lago, and Vila Real de Santo António. The study quantified the irrigation needs of the golf courses, the availability of APR, the nutrients (N and P) provided by APR and the corresponding reduction in synthetic fertilizer use, the carbon emissions associated with irrigation using natural water/APR, and the cost differences related to introducing APR into irrigation.

Although preliminary, the results indicate that APR shows strong potential for use in irrigating golf courses in terms of availability. It could fully meet the water demand at Salgados, and supply between 40% to 90% of the needs at the other courses. In addition to reducing the consumption of natural water, the use of APR decreases the need for synthetic nitrogen fertilizers by 10% to 70% and can completely replace phosphate fertilizers, thereby avoiding the emission of 14.5 tons of CO_2e per year across the four studied courses. Economically, the use of APR at Castro Marim and Quinta do Vale represents cost savings, while at San Lorenzo and Salgados, updated APR pricing may increase irrigation costs but offers greater security in its use, in compliance with EU requirements for treated wastewater reuse. Thus, although this study needs further development to incorporate other aspects—such as the use of new electronic tools (including IoT and AI) for optimizing water, energy, soil, turf, and fertilizer management—it is evident that using APR for golf course irrigation in the Algarve enhances the sector’s environmental sustainability. For example, it was demonstrated that the carbon footprint reduction per golf round in the Algarve could reach 198 g CO_2e.

Keywords: APR, sustainability, carbon emissions, water scarcity, nutrient recycling.

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LIST OF ACRONYMS

ACRONYM	**MEANING**
ApR	Água para Reutilização (Water Reuse)
CNIG	Portugal’s National Council of the Golf Industry
EU	European Commission
FAO	Food and Agriculture Organization
GCC	Gulf Cooperation Council
IUWM	Integrated Urban Water Management
IWRM	Integrated Water Resource Management
PE	Population Equivalent
RO	Reverse Osmosis
UV	Ultraviolet
UWC	Urban Water Cycle
UNESCO	United Nations Educational, Scientific and Cultural Organization
WWAP	World Water Assessment Programme
WWTP	Wastewater Treatment Plant

LIST OF SYMBOLS

Symbol	Term
CO_2	Carbon dioxide
e	Emission
€	Euro
g	Grams
ha	Hectares
kg	Kilogram
$\leq$	Less than
L	Litres
m^3	Cubic meter
N	Nitrogen
N	North
W	West
P	Phosphorus
%	Percentage

Greek letters	
θ	Shelf-life time (days)

I. INTRODUCTION

I.1. Urban Water Cycle

I.1.1. Definition

The Urban Water Cycle (UWC) refers to the complex interaction between water and various hydrological processes within urban environments, including water supply, treatment, distribution, consumption, wastewater collection, and reuse. These processes occur in urban or partially urban areas, integrating both natural and engineered water systems to meet the demands of growing populations while ensuring sustainability (Peña-Guzmán et al., 2017).

The Urban Water Cycle (UWC) is driven by four primary inputs: water, contaminants, energy, and chemicals.

The most fundamental input is water, which enters the system through two main sources: natural supply sources (such as surface water and groundwater) and precipitation. These water inputs form the basis for calculating hydrological balances and consumption within the UWC (Peña-Guzmán et al., 2017).

The second input, contaminants, is closely associated with water movement, as water acts as a transportation medium for pollutants. Contaminants enter the urban water cycle through various pathways, including surface and groundwater flows, wastewater generated from residential and industrial use, treated wastewater discharges, and stormwater runoff, which can carry pollutants from the atmosphere, urban surfaces, and chemical residues (Peña-Guzmán et al., 2017).

The third input, energy, plays a crucial role in water cycle operations, influencing costs and environmental sustainability. Energy is required for water treatment, supply, distribution, and wastewater management. Additionally, thermal water heating contributes to overall energy consumption. During wastewater treatment, biogas can be produced through the breakdown of organic matter, offering a potential renewable energy source (Peña-Guzmán et al., 2017).

The fourth and final input, chemicals, is used in both drinking water purification and wastewater treatment. These chemicals are essential for maintaining water quality standards but also introduce operational costs and potential environmental or health concerns related to their use and disposal (Peña-Guzmán et al., 2017).

While these four inputs shape the UWC, their behavior and interactions are further influenced by external and internal factors, including climate, environmental regulations, economic conditions, and technological advancements (Peña-Guzmán et al., 2017).

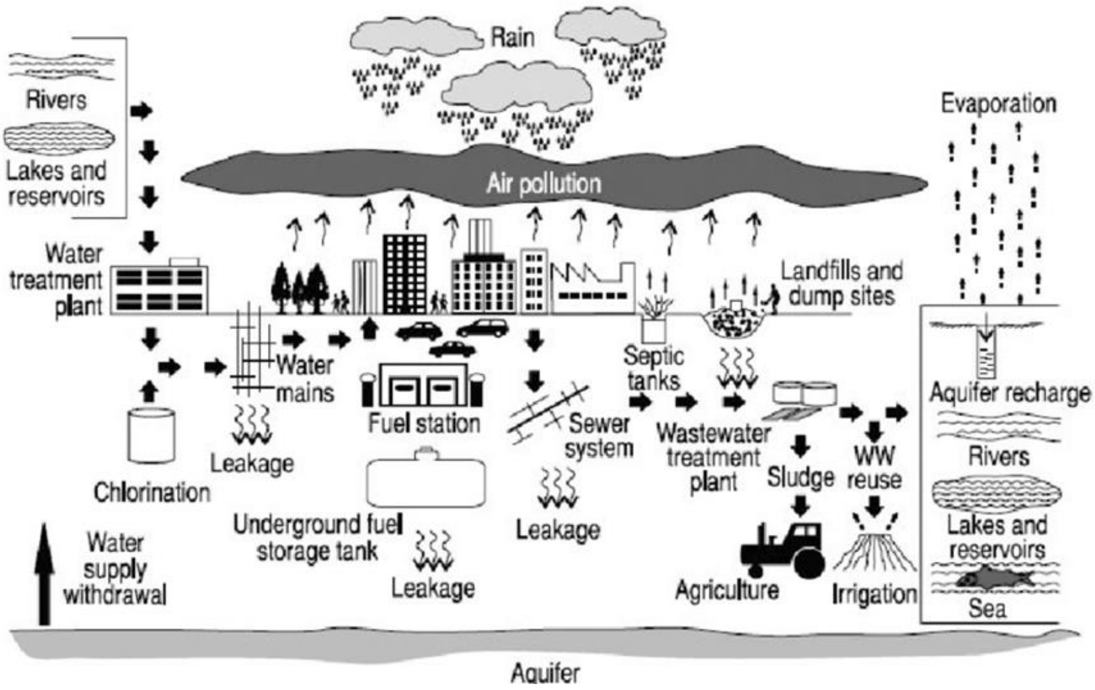


Figure 1.1. Urban Water Cycle (Marsalek et al., 2007)

I.1.2. Evolution

Historically, the urban water cycle was directly related with water extracted, used, and discharged without significant consideration for reuse or sustainability. However, as urbanization and population growth increased, this approach became unsustainable (Capodaglio., 2019).

The evolution of urban water systems has been central to the development of cities, shaping their structure, function, and services over time. Historically, many industrial cities were located near rivers and coasts, where water provided essential resources for transportation, power, and trade. During the Industrial City era, urban waterways were heavily impacted by manufacturing and industrial discharges, leading to widespread pollution and ecological degradation (Kaushal et al., 2015). As populations grew and public health concerns increased, cities transitioned into the Clean City model. This period was marked by the development of centralized water supply and sewage infrastructure, driven by urban selective pressures for clean drinking water and improved sanitation. For example, in Paris, the sewer network expanded dramatically from 570 km to 1240 km between 1877 and 1914 to address sanitation challenges (Kaushal et al., 2015).

In recent years, a further transition towards the Sustainable City has emerged, emphasizing green infrastructure, ecosystem restoration, and integrated water management. Cities are now adopting strategies such as stormwater management systems, nutrient removal technologies in wastewater treatment plants, and urban stream restoration projects. These measures reflect a shift from purely reactive management of water problems to proactive and predictive planning aimed at resilience and sustainability (Kaushal et al., 2015).

Water and urban environments have evolved together through complex relationships that change over time and across different locations, following dynamic and nonlinear patterns. In recent year, these interactions have deepened as urban communities have grown increasingly reliant on water, initially to meet essential needs and later to support large-scale production and the rising demand for water-dependent goods and services (Ridolfi, 2014).

According to the latest World Water Development Report (UNESCO-WWAP, 2024) Global freshwater consumption has been steadily rising by nearly 1% annually, driven by socio-economic growth and shifts in consumption habits, including dietary changes. Agriculture remains the main user, accounting for about 70% of global freshwater withdrawals, while industrial and domestic sectors contribute roughly 20% and 10%, respectively. As economies develop, urban populations expand, and water infrastructure improves, the demand for freshwater increases.

However, rapid population growth has an impact on overall water demand, as the highest population growth rates are often in regions with the lowest per capita water use. Currently, around half of the world’s population experiences significant water scarcity for part of the year, with one-quarter facing extreme water stress, utilizing over 80% of their available freshwater resources. In lower-income nations, inadequate wastewater treatment leads to poor water quality, whereas in wealthier countries, agricultural runoff poses the greatest challenge.

Despite these issues, global water quality data remains limited, particularly in underdeveloped regions of Asia and Africa where monitoring capabilities are weak (UNESCO-WWAP, 2024). Emerging water contaminants of concern include per- and poly-fluoroalkyl substances (PFAS), pharmaceuticals, industrial pollutants, cyanotoxins, and antimicrobial residues from untreated wastewater, livestock farming, and aquaculture, which have been detected across all regions (UNESCO-WWAP, 2024).

The frequency and severity of extreme weather events, such as prolonged droughts and record-breaking rainfall, have increased globally. Climate change is expected to further disrupt the water cycle, intensifying both droughts and floods. The most vulnerable communities, including those in least developed nations, small island states, and the Arctic, are likely to suffer the greatest consequences. As of 2022, 2.2 billion people still lacked access to safely managed drinking water, with four out of five of those affected living in rural areas. Additionally, 3.5 billion people were without access to proper sanitation services. Rapid urbanization has outpaced the ability of cities and municipalities to expand essential water and sanitation infrastructure (UNESCO-WWAP, 2024).

I.1.3. The New Approach in the Mediterranean Region

The Mediterranean region has faced severe water scarcity due to climate change, limited freshwater resources, and growing demand. This has required a shift toward a more circular approach to water management, where wastewater is treated and reused to reduce reliance on freshwater sources. The Mediterranean region, mainly in European countries, has been at the forefront of adopting innovative water management practices, including wastewater reuse. Countries such as Spain, Portugal, France, Malta, and Italy have implemented advanced treatment technologies and policies to promote the reuse of treated wastewater for agricultural irrigation, landscape watering, and industrial processes (Libutti et al., 2018). This evolution reflects a broader global trend toward integrated water resource management (IWRM), which emphasizes efficiency, sustainability, and the use of alternative water sources.

The Mediterranean region is experiencing environmental degradation at an unusual rate (Ksibi et al., 2021a). This crisis is primarily driven by climate change, escalating pollution, rapid urban expansion, and the unsustainable exploitation of natural resources by population growth (Ghorbal et al., 2021). The consequences are evident in various indicators, including rising temperatures, increased frequency of extreme weather events, prolonged droughts, water scarcity, depletion of natural resources, shifts in land use, landscape deterioration, declining

agricultural productivity, biodiversity loss, ecosystem degradation, coastal erosion, rising sea levels, and ocean acidification (Ghorbal et al., 2021). To address these issues, new approaches and strategies have been developed to promote water sustainability, particularly through Integrated Water Resource Management (IWRM) and Technological Advancements.
The key approaches being implemented in the Mediterranean region.

I.1.3 a) Integrated Water Resource Management (IWRM)

The Mediterranean region has been adopted mainly in European countries Integrated Water Resource Management (IWRM) as a holistic approach to water sustainability. IWRM emphasizes the efficient use of water resources, balancing the needs of different sectors (e.g., agriculture, industry, and domestic use) while ensuring environmental protection (Ghorbal et al., 2021).

- **Water-Energy-Food Nexus**: The FAO's Water-Energy-Food Nexus approach is being applied to address the interconnected challenges of water scarcity, energy production, and food security. This approach promotes the sustainable management of resources by considering the interdependencies between these sectors (Flammini et al., 2014).

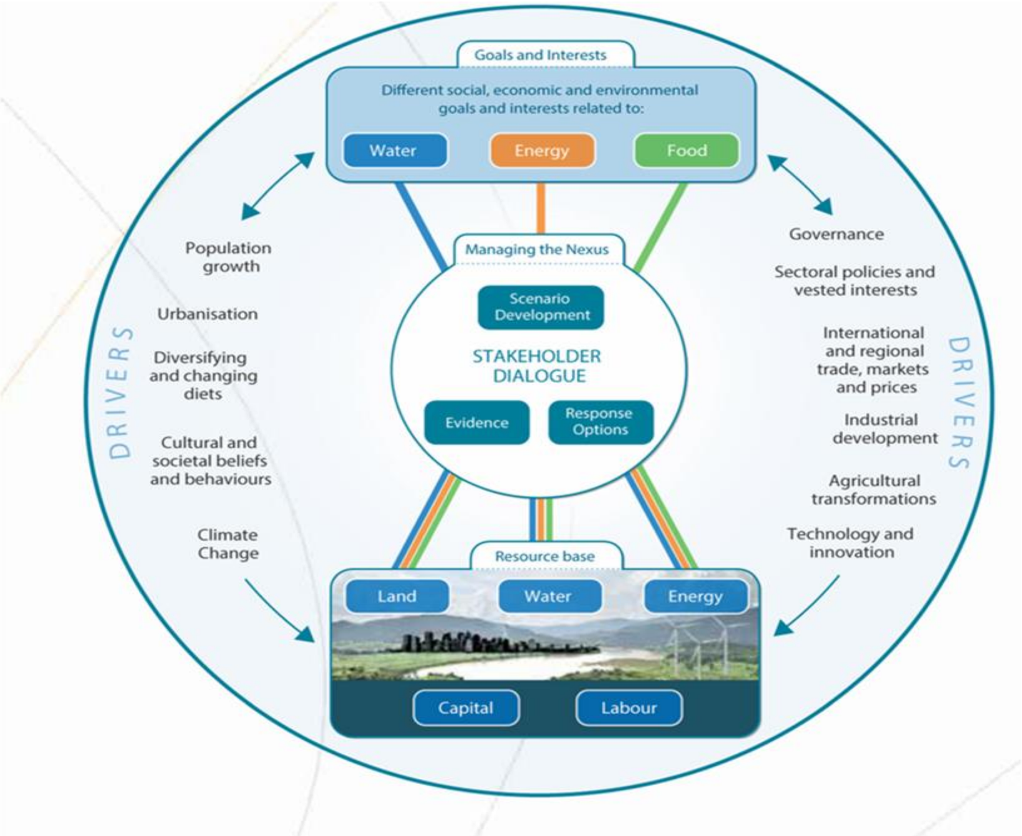


Figure 1.2. The FAO approach to the Water-Energy-Food Nexus (Flammini et al., 2014)

I.1.3 b) Advanced Water Treatment Technologies

The Mediterranean region has invested in advanced water treatment technologies to improve water quality and enable the safe reuse of wastewater. These technologies include:

- **Membrane Filtration and Reverse Osmosis (RO):** A water recycling system has been documented using RO technology for the treatment of wastewater (Almeida, R., 2022). Instead of discharging industrial effluents into rivers and streams, reverse osmosis (RO) membranes can be used to treat the wastewater and reuse for irrigation purposes. The typical operational mode for full-scale RO systems involves crossflow filtration with a high internal flow rate and concentrate recirculation. Common module configurations in RO systems include tubular, spiral wound, hollow Fiber, and disc tube designs (Yang et al., 2020). Among these, the spiral wound module is the most widely used due to cost-effectiveness. These modules follow a standardized design and come in standard diameters of 2.5, 4, and 8 inches to fit into pressure vessels, which can accommodate multiple modules connected in series using O-rings (Simonič, M., 2021). The design consists of flat sheet membranes wrapped around a central tube, with three edges sealed over a permeate spacer to create 'leaves.' The permeate spacer provides structural support for the membrane while facilitating the movement of permeate toward the central tube (Maynard & Whapham, 2020). Spiral wound RO systems are typically used as independent units, and depending on the required effluent quality, multiple filtration stages can be integrated. In such cases, wastewater undergoes two or more filtration steps before being discharged (De Almeida et al., 2020).

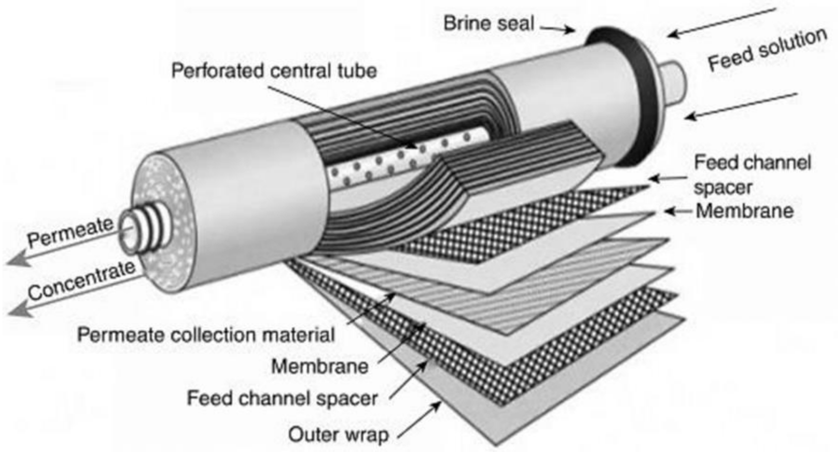


Figure 1.3. Spiral wound module design (Maynard and Whapham, 2020)

I.1.4 Main Problems in Urban Water Cycle Currently

The urban water cycle is facing increasing challenges due to a combination of environmental, social, and infrastructural pressures. Some of the main issues include:

- **Water Scarcity and Climate Change:** Rapid urbanization and population growth are increasing water demand, while climate change is increasing droughts and reducing freshwater availability. Seasonal and inter-annual rainfall variability makes it difficult to forecast water availability and implement efficient management strategies (Iglesias et al., 2007).
- **Pollution and Water Quality Degradation:** Urban wastewater, agricultural runoff, and industrial discharge contribute to poor water quality. In many developing regions, inadequate wastewater treatment leads to contamination of water sources, while in industrialized areas, pollutants such as pharmaceuticals and microplastics pose significant risks (Simonič, M., 2021)
- **Infrastructure Deficiencies:** Aging and insufficient water infrastructure in many cities leads to inefficiencies, high leakage rates, and limited capacity to meet growing demands. Many urban areas struggle to finance necessary upgrades for sustainable water supply and wastewater management (Almeida, R., 2022)
- **Water Governance and Management Challenges:** lack of policy and lack of coordination among multiple stakeholders often lead to ineffective water resource management. Conflicts arise between agricultural, industrial, and domestic users, making it difficult to allocate water equitably and efficiently (Iglesias et al., 2007)
- **Rising Demand from Urbanization and Tourism:** The expansion of cities and the growing tourism industry e.g. golf course place additional stress on local water resources. Tourists often have significantly higher water consumption rates compared to local populations, further straining supplies (Garrote et al., 2005).

I.1.5 Strategies to Address Current Problems in Urban Water Cycle

Addressing the challenges in the urban water cycle requires a combination of technological innovations, policy reforms, and community engagement. The following strategies can help create a more sustainable and resilient urban water system:

I.1.5 a) Efficiency in Water Usage

Water efficiency is a critical component of sustainable water management, particularly in the face of increasing global water scarcity and demand. Efficient water use is necessary to ensure the sustainability of resources while maintaining the ecological balance of water-dependent systems. Rapid urbanization, industries(tourism), and agriculture represent the primary domains where water efficiency measures must be implemented to mitigate waste and enhance resource utilization (Hoekstra & Chapagain, 2007). Climate change, population growth, and increased water consumption increase the challenges of water management, making efficiency strategies crucial in securing water for future generations (Van Leeuwen et al., 2012).

Water efficiency refers to the optimized use of water resources to accomplish the desired function with minimal waste. Unlike water conservation, which focuses on reducing water consumption, efficiency emphasizes the productive use of every unit of water extracted from natural sources (Jenerette & Larsen, 2006). The concept is fixed in the broader framework of Integrated Urban Water Management (IUWM), which integrates technology and policy-driven approaches to balance water supply and demand while considering environmental and socio-economic factors (Van Leeuwen et al., 2012). Integrated Urban Water Management (IUWM) highlights the importance of planning, wherein water efficiency is integrated with energy efficiency, stormwater management, and wastewater reuse to create a sustainable urban water cycle (Frijns et al., 2009). The assessment of water efficiency is performed using several key indicators, including, Water System Leakages – The percentage of water lost in distribution networks, which is a direct measure of infrastructure efficiency (European Green City Index, 2009). High levels of leakage indicate outdated or poorly maintained infrastructure, leading to unnecessary losses. Water Footprint – A measure of total water consumption, including direct and virtual water use, which indicates overall efficiency in water utilization (Hoekstra et al., 2009).

The water footprint accounts for the volume of freshwater used to produce goods and services, making it an essential metric for sustainable consumption. Per Capita Water Consumption – The volume of water consumed per individual, which helps evaluate efficiency at the household and municipal levels (Notovny, 2010). Countries with lower per capita consumption tend to have more efficient water management practices. Reuse and Recycling Rate – The proportion of wastewater treated and reused, indicating the extent to which water is efficiently circulated within systems (Frijns et al., 2009). Cities that integrate wastewater recycling can significantly reduce their demand for freshwater resources.

I.1.5 b) Finding Alternative Water Source

With increasing pressure on conventional freshwater supplies, alternative water sources such as wastewater reuse, desalination, and rainwater harvesting are gaining prominence. These Alternatives can provide viable solutions to enhance water self-sufficiency, particularly in Mediterranean regions which face water scarcity (Rygaard et al., 2010).

Wastewater reuse has emerged as sustainable solutions to augment water supply while reducing environmental pollution. Treated wastewater can be utilized for irrigation, industrial processes, and even potable applications through advanced treatment technologies (Rygaard et al., 2010). Reuse systems reduce the demand on freshwater resources, lower wastewater discharge into natural ecosystems, and contribute to circular water management strategies. The use of reclaimed wastewater for irrigation and groundwater recharge, in both urban and non-urban areas, is growing globally. Numerous water reuse initiatives are already operational in the USA, Japan, and Australia, with their numbers expanding quickly (European Commission, 2006). While the EU currently has fewer wastewater reclamation projects, it holds significant potential for future development in this sector (Hochstrat et al., 2006). In urban settings, wastewater reclamation can be categorized into non-potable reuse, indirect potable reuse, and direct potable reuse.

Desalination is a process that converts seawater or brackish water into potable water through techniques such as reverse osmosis and thermal distillation. This method is particularly beneficial in Mediterranean regions with limited freshwater availability. Desalination has been in use for many years, with the world's total installed capacity now surpassing 60 million cubic meters per day (Eke et al., 2020). The largest desalination facilities currently in operation rely on thermal seawater desalination and are in the Middle East, where individual plants can produce over 500,000 cubic meters daily (Eke et al., 2020). Meanwhile, the biggest reverse osmosis desalination plant, with a capacity exceeding 270,000 cubic meters per day, is found in Israel (Tal, 2006). In Gulf Cooperation Council (GCC) nations, desalination provides two-thirds of the domestic water supply (Dawoud, 2006). While desalination provides a reliable and independent water source, it poses challenges including high energy consumption, environmental concerns related to brine disposal, and infrastructure costs (Rygaard et al., 2010). Innovations in energy-efficient desalination technologies and sustainable brine management strategies are essential for enhancing its feasibility as a large-scale water supply solution.

Rainwater harvesting involves collecting and storing rainwater for various applications, including irrigation, domestic use, and groundwater recharge. This method is cost-effective, reduces dependency on municipal water systems, and mitigates urban flooding. Simple rainwater collection systems, such as rooftop catchments and storage tanks, can be implemented at the household level, while large-scale projects can enhance water security in urban areas (Rygaard et al., 2010). Despite its benefits, rainwater harvesting depends on climatic conditions, requiring appropriate storage and filtration technologies to maintain water quality and reliability.

In summary, the following strategies can help create a more sustainable and resilient urban water system:

Improving Water Efficiency and Conservation

- Implement water-saving technologies, such as low-flow appliances and smart irrigation systems, to reduce unnecessary consumption.
- Promote water conservation awareness campaigns to encourage responsible water use among residents and industries.
- Adopt leak detection and repair programs to minimize water losses in aging infrastructure (Iglesias et al., 2007).

Enhancing Wastewater Treatment and Reuse

- Expand and modernize wastewater treatment facilities to improve water quality before discharge.
- Encourage water reuse and recycling in industrial and agricultural sectors to reduce dependency on freshwater sources.
- Implement decentralized water treatment systems for localized purification, reducing pressure on central facilities (Simonič, M., 2021).

Investing in Resilient Water Infrastructure

- Upgrade outdated pipelines, reservoirs, and water distribution networks to withstand growing urban demands.
- Implement smart water management systems that use real-time monitoring and data analytics to optimize water distribution.
- Integrate nature-based solutions, such as green roofs, rain gardens, and wetlands, to enhance water retention and reduce flood risks (Almeida, R., 2022).

Strengthening Water Governance and Policy Frameworks

- Develop integrated water resource management (IWRM) strategies that align the needs of different sectors, including agriculture, industry, and domestic use.
- Enforce stricter pollution regulations and incentives for industries to adopt sustainable water practices.
- Improve cooperation between municipalities, national governments, and international organizations to implement sustainable water policies (Iglesias et al., 2007).

I.2. Wastewater Reuse

I.2.1 Historical Background

Wastewater reuse has been a fundamental practice throughout human history, improving alongside advancements in water treatment technologies. Initially, untreated wastewater from urban areas with the objective of diverting human waste outside of urban settlements, and land application of domestic wastewater is an old and frequent practice (Angelakis & Snyder, 2015).According to Angelakis & Snyder, 2015 early civilizations, including the Mesopotamians, Indus Valley inhabitants, and Minoans, utilized wastewater for irrigation during the Bronze Age (circa 3200–1100 BC). The practice was later adopted by the Hellenic and Roman civilizations, where wastewater was used for disposal, irrigation, and fertilization (Angelakis et al., 2022). By the 16th and 17th centuries, wastewater reuse in agriculture was formalized through "sewage farms," such as those in Bunzlau (Silesia) and Edinburgh (Scotland). These systems expanded significantly in the 19th and 20th centuries in European and American cities, with Paris being a notable example, where sewage farms processed wastewater for agricultural use (Angelakis & Snyder, 2015).

Modern sewer systems emerged in the mid-19th century as a response to worsening sanitation issues caused by industrialization and urban growth. London, for instance, experienced cholera outbreaks in 1832, 1849, and 1855 due to contaminated water supplies. Additionally, the Great Stink of 1858, when untreated sewage in the River Thames produced unbearable odors, prompted sanitation reforms. Following recommendations by Royal Commissioner Edwin Chadwick, the Metropolitan Commission of Sewers appointed Sir Joseph Bazalgette to design an extensive underground sewage system to safely manage waste (Angelakis & Snyder, 2015).

I.2.2 Modern Applications and Trends

Today, wastewater treatment and reuse projects are expanding in many countries. Treated wastewater is frequently reused for agricultural and landscape irrigation, groundwater recharge, seawater barriers, industrial applications, dual-distribution systems for toilet flushing, and various other urban purposes. Organizations such as the World Bank, the Food and Agriculture Organization (FAO) of the United Nations, and the World Health Organization (WHO) report a steady rise in wastewater reuse, with annual increases of up to 25% in countries like the USA, China, Japan, Spain, Israel, and Australia. For instance, in California, only 860 Mm^3/year of treated wastewater (out of 4300M m^3/year) was reused in 2010, with over 80% (3440M m^3/year) being discharged into the ocean. By 2030, reuse is expected to rise to 2470M m^3/year (Leverenz et al., 2011).

I.2.3 Wastewater Reuse in Europe and Portugal

In Europe wastewater reuse is extremely limited with an average reuse rate of only 2.5 % (European Water Association, 2022). However, some countries in Europe managed to achieve higher rates, such as Cyprus (95 %) and Malta (60 %), with Spain (13 %) and Italy (4 %) (Areosa et al., 2024).

Portugal current reuse rates stand at 1.2 % (ERSAR, 2022), notably low compared with the government targets set to achieve a 10 % reuse rate in 2025 and 20 % by 2030 (Governo de Portugal, 2019). The Algarve region in southern Portugal has implemented strategic measures to significantly increase the use of recycled (waste) water. As of 2025, the region’s annual consumption of treated wastewater stands at approximately 2.1 hm^3(2,100,000m3). Driven by infrastructures and upgrades spearheaded by Águas do Algarve, the regional water authority, this figure is projected to rise to 8.0 hm^3 (8,000,000m^3) by 2026, effectively quadrupling the volume of recycled water utilized in the region (Portugal Resident, 2024a).

This surge in water reuse infrastructure reflects a coordinated effort to lessen dependence on traditional water sources such as reservoirs and groundwater, conserving resources essential for public supply and ecosystems. Key projects include the inauguration of Zoomarine theme park’s wastewater recycling and reuse system, connected to the Albufeira Poente WWTP, exemplifying the region’s approach to integrating tertiary-level treatment systems for non-potable reuse purposes (Portugal Resident, 2024b).

Golf courses, which account for a substantial portion of the region's water demand, are central targets for this strategy. Around half of the approximately 40 golf courses in the Algarve are expected to be irrigated with treated wastewater by 2025, supported by a €23 million investment under the Water Efficiency Plan. This initiative alone anticipates increasing treated wastewater usage from 1.4 hm^3 to 8 hm^3 by the end of 2025, with over 70 percent allocated specifically to golf course irrigation (Portugal Resident, 2024c).

The advancement of wastewater treatment technologies, such as membrane bioreactors, electrochemical systems, and bio electrochemical systems, has improved the quality and efficiency of water reuse. However, challenges remain, including public perception, infrastructure costs, and concerns over emerging contaminants like pharmaceuticals and chemical mixtures. Addressing these challenges requires continued investment in advanced treatment systems and public education to ensure sustainable and safe wastewater reuse (Angelakis & Snyder, 2015).

I.3. Case Study

I.3.1 Importance of Golf Tourism

Wastewater reuse shows significant potential for growth in the agricultural and recreational sectors, driven by their high water demands and the essential importance of irrigation in Mediterranean agriculture. In 2015, the agricultural sector alone used about 75 % of Portuguese water resources, similar to other South European countries (FAO, 2024). Developing strategies to enhance water reuse efficiency and resilience is crucial for sustaining golf course irrigation and reducing dependency on external sources.

Golf plays an important role in the Algarve's economy and cultural identity, contributing significantly to the region's tourism, employment, and international reputation. Its importance extends beyond the Algarve, impacting Portugal's national economy

and positioning the country as a global leader in golf tourism. The Algarve is internationally renowned for its world-class golf courses, which attract experts from all over the globe. With over 40 golf courses spread across the region, the Algarve is often referred to as one of Europe's premier golf destinations, representing over 60% of golf activity in the country (CNIG). The Mediterranean climate, landscapes, and proximity to the beaches create a unique setting for golfers, especially during the cooler months in Northern Europe.

According to Portugal’s National Council of the Golf Industry (CNIG) golf tourism forms a substantial part of the Algarve's tourism industry, which accounts for 1.6% of Portugal’s GDP and, created more than 111,000 jobs, with total wages exceeding €2.2 billion and generating €4.2 billion in 2023. Many tourists visit the Algarve specifically to play golf, leading to high occupancy rates in hotels, resorts, and other accommodations. This influx of tourists supports a variety of businesses, including restaurants, transportation services, and retail outlets, boosting the local economy significantly.

I.3.2 Environmental Impact of Golf Courses

Despite its benefits, the golf industry in the Algarve faces challenges, particularly regarding water usage and environmental sustainability. The maintenance of golf courses in a semi-arid climate requires significant water resources, often leading to tensions between tourism demands and water availability. Addressing these challenges, such as through the reuse of treated wastewater for irrigation, presents an opportunity to make industry more sustainable and resilient in the face of climate change.

I.3.3 Overview of Selected Golf Courses

The four golf courses to be studied are Salgados, Castro Marim, San Lourenço, and Quinta do Vale. These courses are renowned for their decent landscapes and high standards, which make them attractive destinations for both local and international golfers. However, maintaining such landscapes comes at a high environmental cost due to the high water demands for irrigation.

1.3.3 a) Salgados Golf Course

Figure I.4. The Area view of Salgados Golf Course (Salgados Golf Course, n.d.)

Salgados Golf Course, positioned along Salgados Beach and Salgados Lagoon Nature Reserve in western Algarve near Albufeira (37.09325° N, −8.32414° W), covers an irrigated area of 56 hectares. Within this total, 54 hectares are allocated to tees, fairways, and roughs, and 2 hectares are greens.

1.3.3 b) San Lorenzo Golf Course

Figure I.5. The Area view of San Lorenzo Golf Course (San Lorenzo Golf Course, n.d.)

San Lorenzo Golf Course, located within the Ria Formosa Estuary and Nature Reserve, Almancil in the central Algarve (37.06494° N, −8.01501° W), comprises a total irrigated area of 40 hectares. Of this, 38 hectares are dedicated to tees, fairways, and roughs, while 2 hectares are greens.

1.3.3 c) Castro Marim Golf and Country Club

Figure I.6. The Area view of Castro Marim Golf Course (Castro Marim Golf & Country Club, n.d.)

Castro Marim Golf and Country Club, located in the eastern Algarve close to Guadiana River and Atlantic Ocean (37° 14′ 9″ N, −7° 28′ 9″ W), covered 76 hectares of which 30 hectares are irrigated: 27 hectares of tees and fairways, and 3 hectares of greens.

1.3.3 d) Quinta do Vale

Figure I.7. The Area view of Quinta Do Vale Golf Course (Quinta do Vale Golf Resort, n.d.)

Quinta do Vale Golf Resort, situated near the Guadiana River close to the Spanish border (37° 14′ 50″ N, −7° 27′ 2″ W), has an irrigated area of 38 hectares. Of this total, 35 hectares are tees, fairways, and roughs, and 3 hectares are greens.

I.4 Characterisation of Wastewater Treatment Plants (WWTP)

I.4.1.a). Albufeira Poente WWTP

Figure I.8. The Area view of Albufeira Poente WWTP (Águas do Algarve, 2025)

The Albufeira West Intermunicipal WWTP, located in the parish of Guia in the municipality of Albufeira, serves the municipalities of Albufeira, Silves, and Lagoa. The facility was designed to serve 133,900 Population Equivalent (PE) on its design horizon, corresponding to an average daily flow of 28,119 m³/day. Its interceptor system extends approximately 45 km, comprising 15 pumping stations that convey wastewater to the treatment facility (Águas do Algarve, 2025).

The treatment process encompasses preliminary, biological, physicochemical, and disinfection stages, with an additional filtration and UV disinfection step for producing service water. Preliminary treatment includes gross effluent elevation, mechanical screening, and grit/grease removal. Biological treatment is carried out using an activated sludge system under prolonged aeration, with nitrification–denitrification occurring in three biological reactors with alternating anoxic and aerobic zones. These reactors are connected to three secondary clarifiers, forming three complete treatment lines. Phosphorus is removed chemically by adding a coagulant directly into the biological reactors. The biologically treated effluent then undergoes ultraviolet disinfection through three independent lines.

Part of the treated effluent is directed to sand filters, stored in a dedicated reservoir, and further disinfected with UV radiation in a closed duct system to produce service water for reuse within the facility. The fraction of effluent not reused on site is discharged into the Ribeira de Espiche. The solid phase treatment consists of two lines of gravity thickening and sludge dewatering by centrifugation, with the final sludge stored temporarily in silos. Odor control is achieved through a comprehensive system of ventilation and stale air extraction, covering odor-generating units. The extracted air is pre-treated in a vertical wash tower, where conditions of humidity, temperature, and pH are optimized, and subsequently treated in a biofilter using biological deodorization (Águas do Algarve, 2025).

I.4.1.b). Quinta do Lago WWTP

Figure I.9. The Area view of Quinta do Lago WWTP (Google Map)

The Quinta do Lago WWTP is designed to treat effluent from the villages of Almancil, Vale do Lobo-Dunas Douradas, Vale dp Garrão and Quinta do Lago, which corresponds to a population of 27,000 p.e., a flow of 7,863m3/day and an organic load of 1,415 kg BOD_5/day.

The facility is equipped with tertiary treatment for Nitrogen removal, as well as disinfection by ultraviolet (UV) system in order to comply with the following quality standards: 25 mg/l BOD_5, 125 mg/l COD_5, 35 mg/l SST, 15 mg/l Nt, 10 mg/l Pt and 2,000 NMP/100 ml *E. coli.* The treated effluent has been used for more than 20 years to irrigate the São Lourenço golf course and green spaces, and the remainder is discharged into the Corgo do Gondra stream (Águas do Algarve, 2025).

Biological treatment consists of activated sludge systems, followed by a biofiltration and UV disinfection system in prolonged aeration with nitrification/denitrification and biological and chemical removal of Phosphorus, materialized through two biological reactors and two secondary decanters, constituting two treatment lines.

The raw effluent to the WWTP is subjected to a preliminary treatment, which includes a harrowing of the larger solids and the desanding/degreasing of the sands and fats.

Then, the wastewater is sent to two activated sludge lines, one with an oxidation ditch configuration and the other with an aerobic tank operating under medium load, the latter receiving about 90% of the flow. At this stage, organic matter is essentially removed. After secondary decantation, the effluent goes to the tertiary treatment stage – biofiltration – for Nitrogen removal. Ammonia Nitrogen is oxidized to nitrites and nitrates by nitrifying biofilters, followed by its reduction to gaseous Nitrogen in denitrifying biofilters, through the addition of an external carbon source - methanol.

For the sludge accumulated in the secondary decanters, one fraction is recirculated to biological treatment, and the other is subjected to additional treatments, namely gravity thickening and mechanical dewatering in a centrifuge.

The WWTP also has two deodorization systems: one by biofiltration to treat the contaminated air from the primary decanter and the other through chemical washing towers for the treatment of contaminated air that is extracted from the entrance construction buildings and from the sludge dewatering, as well as from the thickener and the runoff circuit of the sludge line.

Currently, the WWTP is being intervened to increase the quality and quantity of ApR that can be supplied for irrigation of more golf courses and green spaces in Quinta do Lago (Águas do Algarve, 2025).

In accordance with the provisions of Decree-Law No. 119/2019 of 21 August, the WWTP will produce ApR class B, i.e., BOD5 ≤ 25 mg O2/L, TSS ≤ 35 mg TSS/L; Escherichia coli ≤ 100 CFU/100mL.

The ApR treatment system involves a chemical disinfection stage using sodium hypochlorite and a filtration stage by pressure filters in rings, followed by the lifting and adduction stages to the delivery points.

I.4.1.c) Vila Real de St.António WWTP

Figure I.10. The Area view of Vila Real de St. António WWTP (Águas do Algarve, 2025)

Vila Real de Santo António (VRSA) WWTP was designed to receive wastewater from several localities, including Fábrica, Altura, Manta Rota, Monte Gordo, Junqueira, Castro Marim, Monte Fino, Aldeia Nova, Vila Real de Santo António city, and Monte Francisco. These effluents are conveyed through a lifting interceptor system comprising 14 pumping stations and 33 km of pipelines, of which 18 km are pressure mains and 15 km are gravity sewers. With the commissioning of this facility, the service coverage of the municipalities of Vila Real de Santo António and Castro Marim (Águas do Algarve, 2025).

The plant is located on the right bank of the Guadiana River, in the Rato marshland area near the fishing dock. Treated effluent is discharged directly into the Guadiana, with the facility specifically designed to comply with microbiological quality standards, thereby supporting the sustainability of the receiving ecosystem. The WWTP has a design capacity of 20,965 m³/day, corresponding to a projected 58,233 PE (population equivalent) for its planning horizon (Águas do Algarve, 2025).

The treatment process is divided into liquid, solid, and gas phases. In the liquid phase, wastewater undergoes preliminary treatment consisting of fine screening and grit/grease removal, followed by biological treatment in aerated lagoons with recirculation under prolonged aeration, preceded by anoxic basins for denitrification. Secondary sedimentation occurs in circular clarifiers, and final disinfection is carried out by ultraviolet (UV) radiation. In the solid phase, sludge from the clarifiers undergoes mechanical thickening, storage in sludge tanks, dewatering in centrifuges, and final storage in silos. For the gas phase, the facility employs chemical deodorization to minimize Odor impacts (Águas do Algarve, 2025).

I.5. Objective

The global objective of this dissertation is to study the environmental advantages and disadvantages associated with reusing urban wastewater for irrigation on golf courses located in the Mediterranean region. This research will monitor the environmental, economic, and operational implications(emission) of using treated wastewater for golf course irrigation in the Mediterranean region. By Incorporating quantitative data collection and comparative analysis, of the following specific objectives

- Quantify the amount of natural water used for irrigation of these golf courses to be a reference for the amount of treated wastewater that we will need.
- Compare the quality of natural water with the quality of treated wastewater.
- Collect information for the four golf courses about the amount of synthetic fertilizers (N and P) applied with natural water irrigation and compare them with the needs when we have water reuse.
- Compare the carbon emissions related to the use of natural waters with carbon emissions related to wastewater reuse.
- Analize the financial differences related to the introduction of water reuse for irrigation of the studied golf courses.
- Final Considerations for the golf sector, using these golf courses as a case study for the Mediterranean.

II. METHODOLOGY

This study adopted to evaluate the environmental, economic, and operational impacts of reusing treated urban wastewater for golf course irrigation in the Mediterranean region, specifically the Algarve, Portugal. Given the growing pressure on freshwater resources and increasing demand for sustainable practices in recreational landscapes, it focuses on the potential for wastewater reuse to offer a viable alternative to conventional irrigation practices. A case study approach was employed, focus on four golf courses, Salgados Golf Course, San Lorenzo Golf Course, Castro Marim Golf Course, and Quinta do Vale Golf Course, they are selected based on their varying locations, sources of irrigation water, and operational characteristics. The methodology integrates both qualitative and quantitative data, combining information from AdA(Águas do Algarve) and Golf courses, along with comparative analysis, to address six specific research objectives.

II.1. Quantification of Natural Water Use for Irrigation of Golf Courses

II.1.a Data Collection

The quantification of natural water use was based on irrigation records collected from four representative 18-hole golf courses in the Algarve: **Salgados, San Lorenzo, Castro Marim, and Quinta do Vale**. These courses were selected to capture different geographical and management conditions, ranging from coastal to inland locations, and from selective irrigation strategies to more extensive turf coverage.

Monthly and annual irrigation data were provided directly by the respective course management teams and **Águas do Algarve (AdA, 2025)**. The period **2015–2019** was chosen because it represents the most complete and consistent dataset available because it encompasses years with differing hydrological conditions, including both average and drought-prone seasons.

The irrigation sources were identified as **groundwater abstraction (furo)** or **surface water storage (barragem)**, reflecting the traditional supply methods used in the Algarve golf sector. No courses within the sample were using treated wastewater during the study period, which makes these records an accurate baseline of natural water dependence. **Figure II.11** presents monthly irrigation demand patterns for a typical 18-hole course, The peak consumption is observed in July and August, reaching around 70–75 × 10^3 m^3.

To examine irrigation practices in relation to climatic variability, complementary meteorological data were obtained. **Figure II.12** shows Monthly average precipitation (mm) and average temperature aligns with higher temperatures and evapotranspiration rates.
Monthly averages of **precipitation (mm)** and **air temperature (°C)** for the Algarve between **2010 and 2022** were extracted from the regional climate datasets presented by **Zepner et al. (2020)**. This climate dataset allowed for the establishment of long-term seasonal patterns against which irrigation demand could be interpreted, particularly in relation to evapotranspiration dynamics.

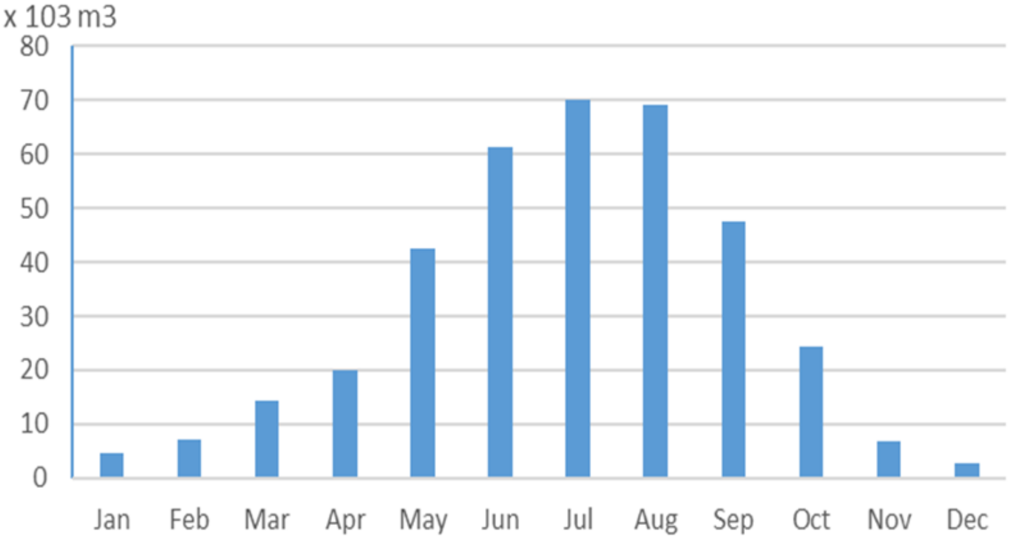
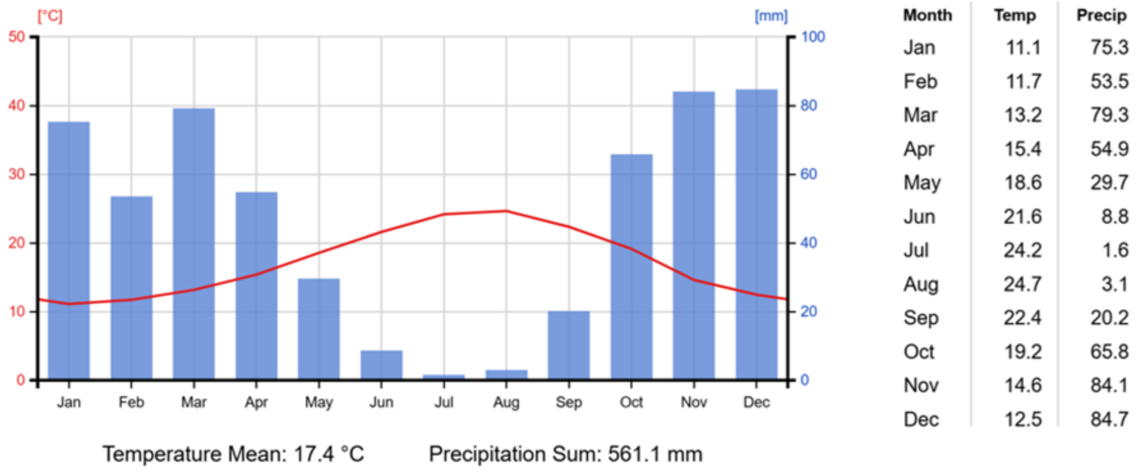


Figure II.11- Average monthly irrigation water consumption per golf course (18 holes) in the Algarve (Nunes and Guerrero, 2022).



Month	Temp	Precip
Jan	11.1	75.3
Feb	11.7	53.5
Mar	13.2	79.3
Apr	15.4	54.9
May	18.6	29.7
Jun	21.6	8.8
Jul	24.2	1.6
Aug	24.7	3.1
Sep	22.4	20.2
Oct	19.2	65.8
Nov	14.6	84.1
Dec	12.5	84.7

Figure II.12- Monthly average precipitation (mm) and average temperature (^{0}C) for Algarve region from 2010-2022 (Zepner et al.2020).

In addition, long-term annual data for the selected golf courses was analyzed (**Figure II.13**), providing a baseline of water use between 200–450 × 10^3 m^3/year.

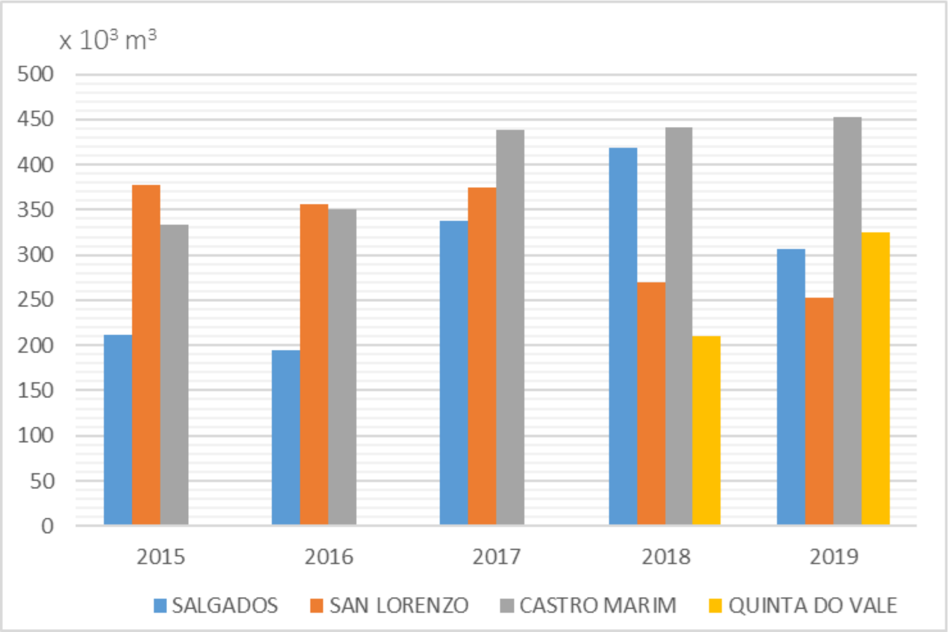


Figure II.13- Water Consumption for Irrigation of the Studied Golf Course (2015-2019)

II.1.b Data Analysis

The irrigation records were organized into monthly time series for each of the four courses. These values were then aggregated into annual totals, allowing both seasonal dynamics and interannual variability to be observed. By presenting monthly consumption alongside precipitation and temperature averages, it was possible to evaluate the sensitivity of irrigation demand to regional climatic forcing.

To enhance comparability among the case studies, irrigation volumes were normalized by irrigated surface area (m^3/ha). This step is important because golf courses vary substantially in size and irrigation strategies: for example, some prioritize only greens and fairways, while others irrigate roughs and peripheral turf. Normalization thus provides a standardized metric for benchmarking efficiency and relative intensity of water use.

In addition, irrigation demand was analyzed in terms of seasonal concentration. The proportion of annual irrigation applied between May and September was calculated, as this period tally with the Algarve's driest and hottest conditions, when turfgrass water requirements are highest.

Further, absolute and relative consumption levels were contrasted among the courses to assess the influence of geographical location (coastal vs. inland), course design, and management practices. For example, inland courses such as Castro Marim, with larger irrigated areas and greater exposure to solar radiation, were expected to show higher demand than coastal courses like Salgados, where relative humidity may reduce evapotranspiration rates.

Finally, long-term annual consumption was examined to provide a baseline reference range of natural water use for Algarve golf courses, estimated at approximately 200–450 × 10^3 m^3 per course per year. This baseline quantification is critical for two reasons: (i) it defines the scale of natural resource dependency within the sector, and (ii) it establishes the benchmark against which the potential substitution of natural water with treated wastewater can later be evaluated in terms of environmental, technical, and economic feasibility.

This consumption data establishes the baseline demand for irrigation water, which is essential for estimating the volume of treated wastewater required to replace natural sources. Data was normalized by course area and irrigation duration.

II.2. Water Quality Comparison: Natural Water vs. Treated Wastewater

II.2.a Data Collection

To evaluate the feasibility of substituting natural water sources with treated wastewater (ApR), production data were collected from the **three main wastewater treatment plants (WWTPs)** supplying the case study golf courses:

- **Albufeira Poente WWTP**, supplying Salgados Golf Course.

- **Quinta do Lago WWTP**, supplying San Lorenzo Golf Course.
- **Vila Real de Santo António WWTP**, supplying Castro Marim and Quinta do Vale Golf Courses.

Monthly records of **treated wastewater availability** for the **reference year 2024** were obtained directly from **Águas do Algarve (AdA, 2025)**. These data capture seasonal variations in ApR volumes linked to regional water consumption patterns, particularly the influence of tourism on wastewater generation.

In addition to volumetric availability, **water quality parameters** were analyzed to assess compliance with reuse standards and irrigation suitability. The parameters monitored at each WWTP, including pH, electrical conductivity, nutrients (Nitrogen and Phosphorus), suspended solids, microbiological indicators (*E. coli*), and residual chlorine.

II.2.b Data Processing and Analysis

The ApR availability data were first compiled into **monthly time series per WWTP**, with annual totals computed for each treatment plant. This allowed the identification of seasonal patterns and annual production capacity.

To assess the potential for reuse in golf irrigation, ApR volumes were compared directly with the **irrigation demand of each case study course** (as established in Section II.1). This comparison was expressed both in **absolute terms (m^3)** and as a **percentage of demand covered by ApR**. The analysis emphasized seasonal dynamics, particularly during **summer months (May–September)** when irrigation requirements peak.

The methodological steps were as follows:

1. **Aggregation of monthly ApR volumes** for each WWTP.
2. **Annual totals** of ApR produce calculated and compared to annual irrigation demand of corresponding golf courses.
3. **Coverage ratios (%)** computed by dividing available ApR by irrigation requirements for each month and year.
4. Identification of **surplus and deficit periods** where ApR exceeded or fell short of demand.

In parallel, the **quality parameters** from **Table II.1** were assessed against European and Portuguese standards for water reuse in agriculture and landscape irrigation (EU Regulation 2020/741; APA guidelines). This ensured that, beyond quantity, the water available is technically suitable for application on turfgrass.

II.3. Nutrients in Treated Wastewater and Synthetic Fertilizer Needs

II.3.a Data Collection

To assess the potential of treated wastewater (ApR) to substitute synthetic fertilizers, data on nutrient concentrations were obtained from **Águas do Algarve (AdA, 2025)** for the three wastewater treatment plants (WWTPs) supplying the case study golf courses: **Albufeira Poente (Salgados), Quinta do Lago (San Lorenzo), and Vila Real de Santo António (Castro Marim and Quinta do Vale)**.

The monitored parameters included **Total Nitrogen (N)** and **Total Phosphorus (P)**, reported as monthly averages (mg/L). Sampling frequency varied by plant and parameter (bi-weekly to monthly), in line with Portuguese regulations for water quality monitoring (see **Table II.1 in page 31**). These concentration values were coupled with the monthly ApR volumes available at each WWTP (**Figure II.10**) to estimate nutrient loads supplied to golf courses during the reference year **2024**.

II.3.b Calculation of Nutrient Loads

Nutrient availability from ApR was calculated by multiplying the monthly treated wastewater volume (m^3) by the corresponding nutrient concentration (mg/L). The result was expressed as **total kilograms of N and P delivered per course per month**.

Theoretical nutrient loading from treated wastewater was calculated using:

Nutrient Load (kg)=Concentration (mg/L) ×Volume (m^3) ×10^{-3}

Where:

- **Concentration (mg/L)** is the average monthly value reported by the WWTP.
- **Volume (m^3)** is the monthly wastewater flow supplied to the golf course.

Annual totals were then obtained by summing the monthly loads, and nutrient supply was normalized by irrigated area (kg/ha.year) to allow comparability across courses of different size.

The results were compared with actual fertilizer application rates to estimate potential reductions in synthetic fertilizer inputs. This analysis helped determine whether nutrient-rich effluent could replace chemical fertilizers.

II.4 Carbon Emissions Avoided with Treated Wastewater Irrigation

II.4.a Data Collection

The avoided carbon emissions associated with treated wastewater (ApR) irrigation were estimated by quantifying the reductions in synthetic fertilizer application enabled by the nutrients supplied in the wastewater. Monthly and annual nutrient loads of **Nitrogen (N)** and **Phosphorus (P)** from ApR were obtained from the three wastewater treatment plants supplying the case study golf courses: **Albufeira Poente (Salgados), Quinta do Lago (San Lorenzo), and Vila Real de Santo António (Castro Marim and Quinta do Vale)** (see Section II.3).

Baseline fertilizer requirements for turfgrass were derived from agronomic literature (Costa et al., 2011; Paranychianakis et al., 2015) and expressed in terms of N and P application per hectare per year. These requirements were then compared with the nutrient contributions from ApR to determine the **potential reduction in synthetic fertilizer demand**.

II.4.b Calculation of Avoided Fertilizer Application

The reduction in fertilizer use was calculated on a monthly and annual basis by subtracting the nutrient loads supplied by ApR from the agronomic fertilizer requirements for each course. If ApR supplied more nutrients than the crop requirement, the excess was capped at the agronomic demand, assuming no further fertilizer reduction beyond the crop needs.

For Nitrogen and Phosphorus, the avoided synthetic fertilizer (kg) was calculated as

Fertilizer reduction (kg N) =min (N load from ApR, N requirement)

Fertilizer reduction (kg P) =min (P load from ApR, P requirement)

II.4.c Carbon Emission Calculation

The carbon footprint associated with synthetic fertilizer production was estimated using **European plant-gate carbon intensities**, following ISO 14067 standards (Moreira da Silva et al., 2020):

- **Nitrogen fertilizer:** 1.14 kg CO_2e per kg N
- **Phosphorus fertilizer:** 0.71 kg CO_2e per kg P

The avoided carbon emissions (CE) were then calculated as:

CE avoided (kg CO_2e) = (N fertilizer avoided×1.14) +(P fertilizer avoided×0.71)

II.5. Cost Comparison of ApR and Natural Water

II.5. a Data Collection

To evaluate the financial implications of substituting natural water by reclaimed wastewater (ApR) in golf course irrigation, detailed cost and consumption data were collected from four representative golf courses in the Algarve: Salgados, San Lorenzo, Castro Marim, and Quinta do Vale. The source of data were:

- **Golf courses -** provided monthly and annual consumptions of water for irrigation (m^3) and related costs (€) over multiple years.
- **Águas do Algarve -** provided data about quantity, quality, and prices or tariff projections for ApR from the studied WWTP.

Where ApR costs were unavailable (e.g., Salgados during the study period), the analysis relied on reported volumes to highlight the potential significance of wastewater reuse, even in the absence of direct financial comparisons.

II.5. b Data Analysis

The comparative cost analysis proceeded in three steps:

a) **Volume Standardization:** Annual irrigation volumes (m^3) were compiled for both natural water and ApR at each golf course. These were normalized by course area (hectares) to enable cross-case comparisons.

b) **Cost Calculation:**

- For natural water, costs were calculated using reported volumes multiplied by the applicable tariffs provided by *Agua do Algarve*.
- For ApR, costs were derived either from existing tariff agreements (e.g., Castro Marim and Quinta do Vale €0.19/m^3) or, where unavailable, from projected tariffs (e.g., San Lorenzo, €0.21/m^3 following the rehabilitation of the Quinta do Lago WWTP).

c) **Comparison of Scenarios:** For each golf course, the cost of natural water was directly compared with ApR for the same or projected volume. Differences were expressed in both **absolute terms (€)** and **relative percentages (%)**, highlighting potential savings or additional costs associated with ApR adoption.

III. RESULTS ANALYSIS AND DISCUSSION

III.1 Quantification of Natural Water Use for Irrigation

The quantification of natural water use in golf course irrigation in the Algarve is showed in **Figure III.14** presents the monthly evolution of irrigation water demand for the four case studies (Salgados, San Lorenzo, Castro Marim, and Quinta do Vale). These results are consistent with the general seasonal change of the region, where irrigation demand is strongly controlled by climate, as illustrated by the average monthly precipitation and temperature trends for the Algarve between 2010–2022 (Figure II.9) (Zepner et al., 2020).

(m^3)

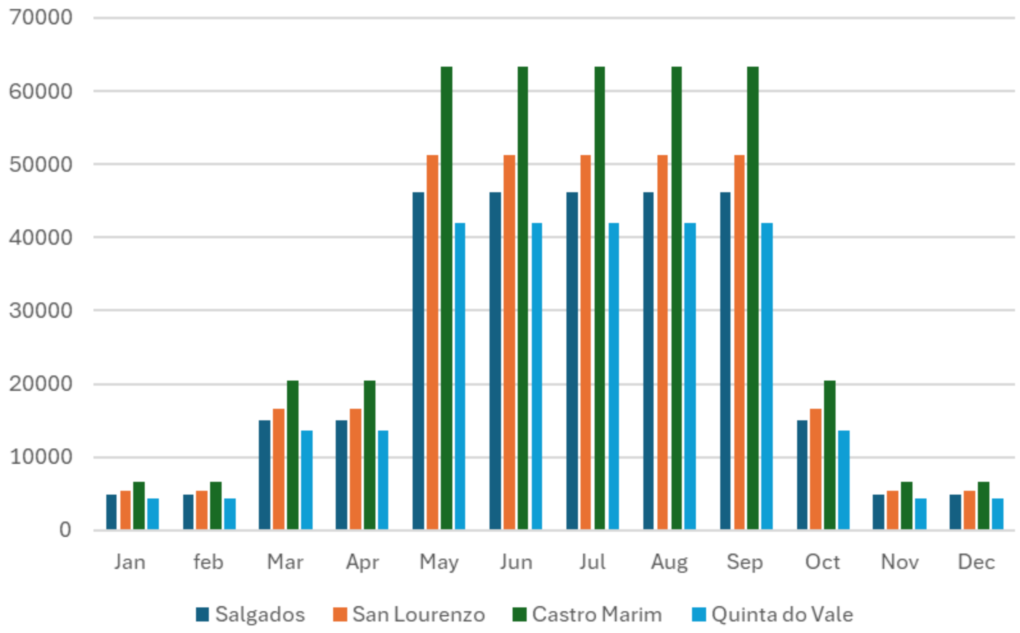


Figure III.14 – Evolution of water demand during the year in the four case studies, according to general trend in Algarve.

All four case studies reveal a pronounced seasonality in irrigation demand, with the lowest consumption recorded during the winter months (December–February), typically below **10,000 m³ per month**. This corresponds to periods of higher rainfall and lower evapotranspiration rates, when irrigation is primarily used for turfgrass maintenance rather than growth. From **March onwards**, irrigation requirements increase significantly, coinciding with declining precipitation and rising temperatures. The highest demands occur between **May and September**, during which each course exceeds **40,000 m³/month**. This five-month peak accounts for **over 70% of the annual irrigation requirement**, reflecting the regional dependency of golf courses on intensive summer irrigation ((Nunes and Guerrero, 2022). The share of irrigation demand during the summer peak was then compared across the four courses to highlight differences in water stress exposure and management approaches.

In comparison between the courses the seasonal pattern is similar, the absolute volumes vary among the four case studies:

a) **Salgados** shows intermediate consumption, peaking at around **46,000 m³/month**. Despite being located near the coast, where humidity may reduce evapotranspiration, its relatively large, irrigated area(56ha) sustains high summer water use.

b) **San Lorenzo** demonstrates similarly high consumption, peaking at approximately **51,000 m³/month**. Its irrigation strategy prioritizes fairways and roughs in addition to play-critical areas, increasing overall demand.

c) **Castro Marim** consistently records the highest demand, surpassing **63,000 m³/month** during summer. Its inland location, extensive irrigated area, and higher exposure to solar radiation contribute to this elevated consumption.

d) **Quinta do Vale** exhibits the lowest consumption, not exceeding **42,000 m³/month**, and maintaining an annual volume of about **240,000 m³**. The course applies a more selective irrigation approach, prioritizing greens and fairways.

The concentration of irrigation demand in the summer months has critical implications for regional water availability. In **July alone**, the combined demand of the four courses exceeds **200,000 m³**, equivalent to the monthly domestic water consumption of approximately **10,000 Algarve residents** (APA, 2021). This overlap with peak agricultural and urban demand raises competition for groundwater resources, which are already under pressure from recurrent droughts and declining recharge.

Climate change projections for the Algarve suggest further reductions in precipitation and increases in evapotranspiration (Zepner et al., 2020), which are expected to increase irrigation demand. The quantification of current use therefore underscores the urgency of diversifying irrigation sources, including the reuse of treated wastewater.

III.2 Availability of Treated Wastewater for irrigation

Treated Wastewater availability in each WWTP – data from AdA

The availability of treated wastewater (ApR) from local wastewater treatment plants (WWTPs) is a critical factor in determining the feasibility of replacing natural freshwater sources in golf course irrigation. **Table III.1** summarizes the main parameters monitored at each WWTP, including pH, electrical conductivity, nutrients, suspended solids, microbiological indicators (E. coli), and residual chlorine. Monitoring frequency varied across parameters, ranging from continuous (e.g., conductivity, turbidity) to monthly or bi-weekly sampling (e.g., Nitrogen, Phosphorus, BOD_5, microbial counts).

Table III.1 – Characteristics of treated wastewater from the main WWTPs supplying the case study golf courses in the Algarve (AdA, 2025)

Parameter	Unit	Albufeira Poente WWTP (Salgados)	Quinta do Lago WWTP (São Lorenzo)	V. Real S. António WWTP (Castro Marim & Quinta do Vale)	Sampling Frequency
pH	Sorensen scale	✓	✓	✓	Bi-weekly / Weekly / Monthly
Electrical Conductivity	dS/m	✓	✓	✓	Bi-weekly / Bi-weekly / Continuous
Turbidity	NTU	✓	✓	✓	Bi-weekly / Bi-weekly / Continuous
Ammoniacal Nitrogen	mg N/L	✓	✓	✓	Bi-weekly / Monthly / Monthly
Total Nitrogen	mg N/L	✓	✓	✓	Bi-weekly / Monthly / Monthly
Total Phosphorus	mg P/L	✓	✓	✓	Bi-weekly / Monthly / Monthly
BOD_5 (CBO_5)	mg/L	25 mg/L	25 mg/L	25 mg/L	Bi-weekly / Monthly / Monthly
Suspended Solids (SST)	mg/L	35 mg/L	35 mg/L	35 mg/L	Bi-weekly / Monthly / Monthly
Bromoform	µg/L	✓	✓	✓	Bi-weekly / Monthly / Monthly
Chloroform	µg/L	✓	✓	✓	Bi-weekly / Monthly / Monthly
E. coli	CFU/100 mL	2,000	2,000	1,000	Bi-weekly/
Parasite Eggs	Nº/L	✓	✓	✓	Bi-weekly
Free Residual Chlorine	mg/L Cl_2	✓	✓	✓	Bi-weekly / Weekly / Bi-weekly

Table III.2 summarizes the monthly volumes available in the reference year (2024) from the three main WWTPs supplying the case study courses: **Albufeira Poente (for Salgados), Quinta do Lago (for San Lorenzo), and Vila Real de Santo António (for Castro Marim and Quinta do Vale)**. **Figure III.12** illustrates the temporal variation of ApR availability, while subsequent figures compare the percentage of irrigation demand that could be met by ApR at each course.

Table III.2 Availability of Treated Wastewater for Reuse (m^3) in reference year (2024).

2024	**Albufeira Poente**	**Quinta do Lago**	**V. R. Sto António** (for Castro Marim)	**V.R. Sto António** (for Quinta do Vale)
Jan	33333	2953	15743	328
Feb	33333	4627	537	327
Mar	33333	11714	366	1577
Apr	33333	27155	604	7143
May	33333	44799	27370	19427
Jun	33333	37431	33711	21450
Jul	33333	41941	27249	22756
Aug	33333	39220	42906	41460
Sep	33333	45806	14439	31622
Oct	33333	13833	*Not available*	*Not available*
Nov	33333	243	391	247
Dec	33333	10685	352	232
Total (m^3)	**399 996**	**280 164**	**161 420**	**145 436**

In general, the data reveal a seasonal pattern in ApR availability. At **Albufeira Poente**, production was relatively stable throughout the year, averaging **33,333 m^3/month**, yielding a total of nearly **400,000 m^3 annually**. In contrast, the **Quinta do Lago WWTP** displayed strong seasonality, with availability peaking in May–August (between **27,000–45,000 m^3/month**) and falling to near-zero in November. Similarly, the **Vila Real de Santo António WWTP** presented significant fluctuations, with peak production in late summer (over **40,000 m³ in August**) but very limited supply in winter months (less than **500 m³ in November–December**).

These seasonal variations are explained by the direct relationship between wastewater production, and regional population increase. Tourism-driven increases in summer produce higher wastewater volumes, while winter off-season results in reduced inflows to WWTPs (APA, 2021). This pattern aligns with other Mediterranean coastal regions where tourism contributes to seasonal wastewater variability (Angelakis and Snyder, 2015).

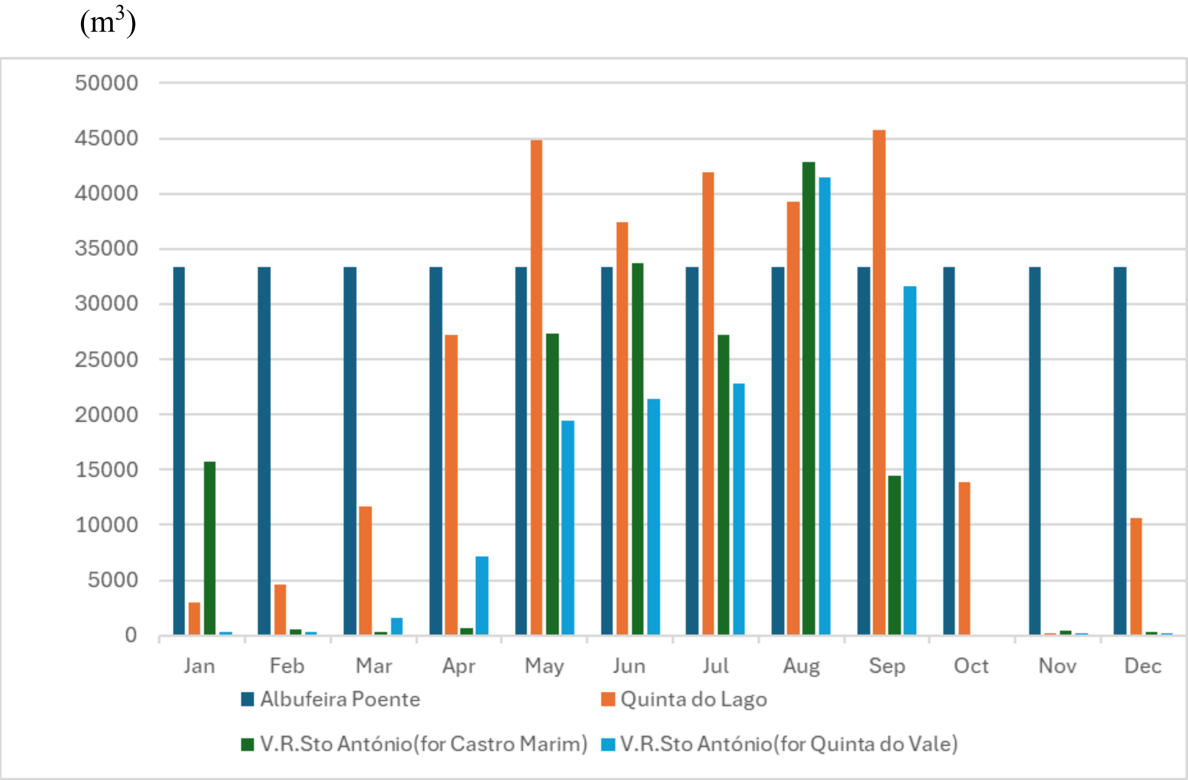


Figure III.15 – Evolution of availability of treated wastewater (ApR) during the reference year (2024) according to data supplied by AdA for the three WWTP.

When compared against the irrigation needs quantified in **Section III.1**, the results show that ApR availability could meet a substantial portion of demand, particularly during the peak summer season when golf courses require the most water:

a) **Salgados (Albufeira Poente WWTP):** With nearly **400,000 m³ annually**, ApR availability comfortably exceeds irrigation demand (~280,000 m³/year). It seems that ApR could supply **100% of irrigation needs** throughout the year.

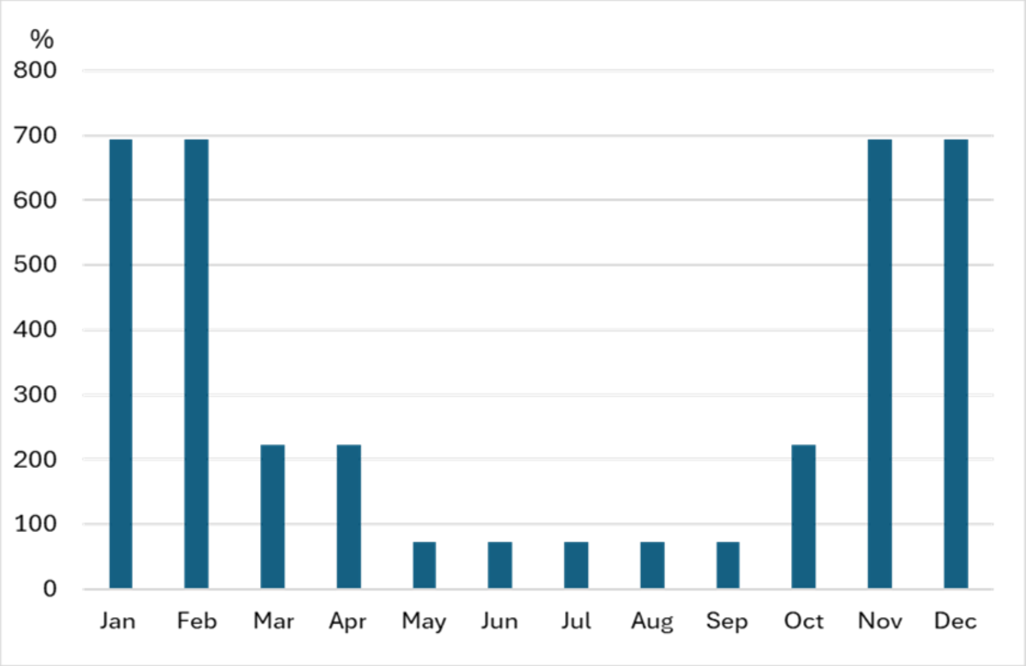


Figure III.16 – % of irrigation with ApR in Salgados Golf Course reference year (2024) according to data supplied by AdA.

b) **San Lorenzo (Quinta do Lago WWTP):** Availability totals 280,164 m³, slightly below annual irrigation requirements (~310,000 m³). While summer months provide sufficient ApR to cover more than 90% of irrigation demand, shortfalls occur in late autumn and winter.

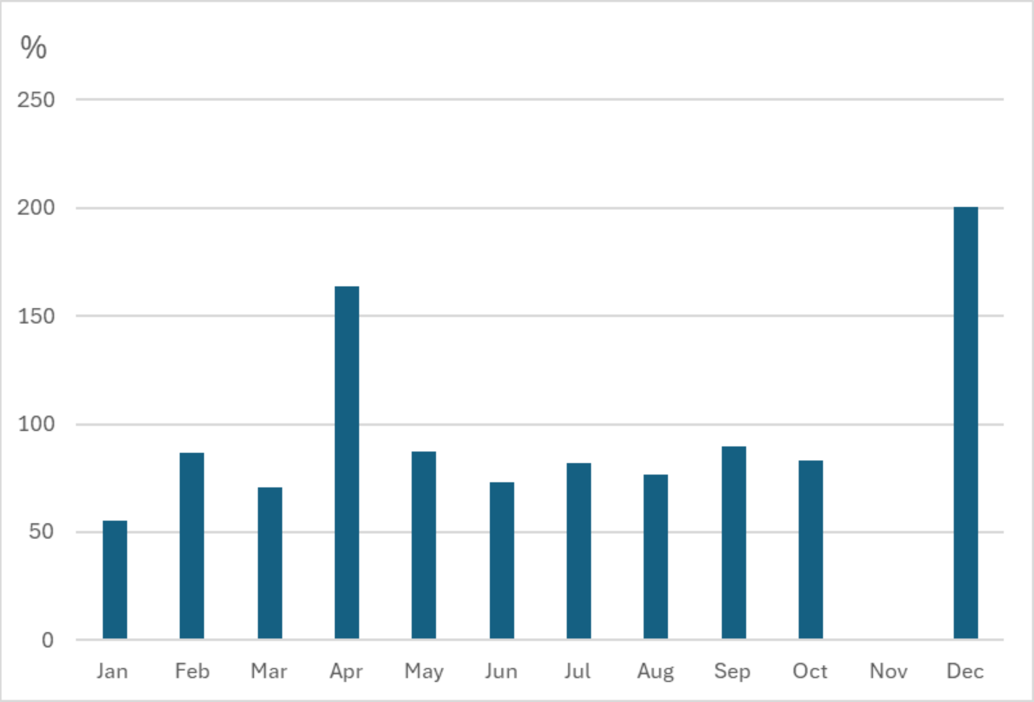


Figure III.17 – % of irrigation with ApR in San Lorenzo Golf Course reference year (2024) according to data supplied by AdA.

c) Castro Marim (V.R. Sto António WWTP): Annual ApR production is approximately 161,420 m³, which represents less than half of irrigation requirements (~370,000 m³). Supply is adequate to cover 40–60% of demand during summer peaks but remains insufficient on an annual basis.

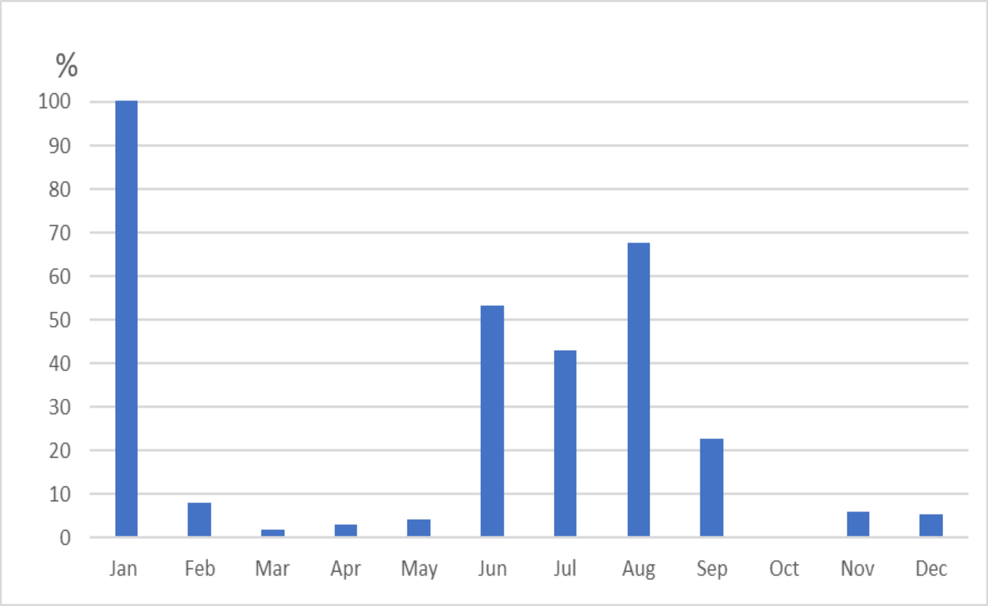


Figure III.18 – Percentage of irrigation with ApR in Castro Marim Golf Course reference year (2024) according to data supplied by AdA

d) Quinta do Vale (V.R. Sto António WWTP): Availability totals only **145,436 m³**, compared to annual irrigation needs of ~240,000 m³. Coverage reaches **up to 60% in peak months**, but significant gaps remain in off-peak periods.

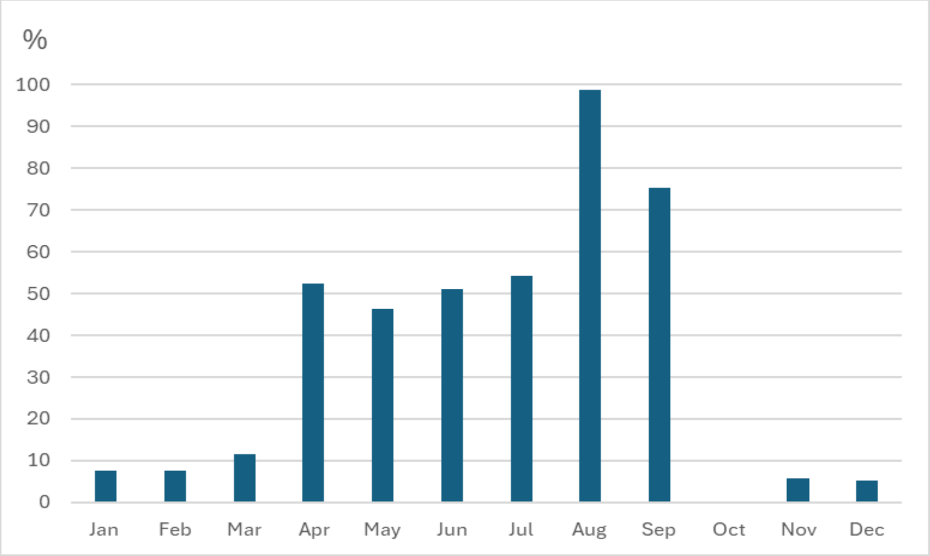


Figure III.19 – Percentage of irrigation with ApR in Quinta Do Vale Golf Course reference year (2024) according to data supplied by AdA.

III.3 Nutrients in Treated Wastewater and Synthetic Fertilizers Need

The integration of treated wastewater (ApR) into irrigation practices not only provides an alternative water source but also contributes nutrients, particularly Nitrogen (N) and Phosphorus (P), that may partially substitute synthetic fertilizers. These two elements are a key advantage of water reuse in irrigation systems of turfgrass, because the decrease not only in the maintenance costs of the turfgrass but also in the environmental impact due to the reduction of carbon emissions (Paranychianakis et al., 2015).

The agronomic requirements for turfgrass vary depending on species and use. Bentgrass (*Agrostis stolonifera*), primarily used on golf greens in the Algarve, has a relatively high nutrient demand, requiring 180–250 kg N/ha/yr and 80–90 kg P_2O_5/ha/yr. Hybrid bermudagrass (*Cynodon dactylon* × *Cynodon transvaleensis*, e.g., Tifway 419), widely used on tees, fairways, and roughs, requires 150–220 kg N/ha/yr and 40–60 kg P_2O_5/ha/yr. Tall fescue (*Festuca arundinacea*), less commonly used, has slightly lower demands of 100–180 kg N/ha/yr and 30–50 kg P_2O_5/ha/yr.

Research by Costa et al. (2011) indicates that to maintain good visual quality, Bermuda grass requires 40-60 kg N/ha/month during the peak growing season (May–September), with a minimum threshold of 20 kg N/ha/month to prevent quality decline. Phosphorus demand is typically higher, often recommended at approximately double the monthly Nitrogen rate (Costa et al., 2011). The analysis of nutrient loads in the four case study courses demonstrates significant variability in nutrient availability depending on the wastewater treatment plant (WWTP).

a) **Salgados**, the Albufeira Poente WWTP provided a relatively constant wastewater flow, amounting to **294,801 m³ annually**. The nutrient content, however, was limited, with annual totals of **1,522 kg/year N** and **107 kg/year P**. On a per hectare basis, this equal to approximately **27 kg N/ha/year** and **2 kg P/ha/year** across the 56 hectares of irrigated area. The water supply is abundant, the nutrient contribution remains limited, covering only about **10–15% of Nitrogen** and **<10% of Phosphorus** needs of Bermudagrass turf, which typically requires **150–250 kg N/ha/year** and **20–40 kg P/ha/year** for optimal quality in Mediterranean golf courses (Costa et al., 2011).

Table III.3 Amount of Total Nitrogen and Total Phosphorus supplied by the Treated Wastewater (ApR) throughout the year in Salgados Golf Course.

	ApR -Albufeira Poente				
Reference year 2024	**Total N ApR m^3**	**ApR N-Total mg/l**	**Total N kg/Golf Course**	**ApR P-Total mg/l**	**Total P kg/Golf Course**
Jan	4807	7.5	36	0	0
Feb	4807	7.0	34	0	0
Mar	14954	7.5	112	0	0
Apr	14954	3.3	49	0	0
May	46143	3.5	161	0	0
Jun	46143	4.4	201	0	0
Jul	46143	5.7	263	0.5	23
Aug	46143	6.0	277	0.7	32
Sep	46143	5.5	254	0.9	42
Oct	14954	5.2	78	0.7	10
Nov	4807	6.0	29	0	0
Dec	4807	6.0	29	0	0
	294801		1522		107
	Total Irrigated Area	**56 ha**			

b) **San Lorenzo** received **327,328 m³ ApR annually**, with a much higher nutrient content of **4,583 kg/year N** and **1,250 kg/year P**. This represents **115 kg N/ha/year** and **31 kg P/ha/year** across 40 hectares. These values indicate that wastewater can substitute up to **50–70% of synthetic Nitrogen** and nearly **all Phosphorus inputs**, particularly during the summer months when nutrient concentrations peaked (e.g., **1,588 kg N in August** at 31 mg/L). The seasonal alignment of nutrient availability with turfgrass growth demand is beneficial, reducing the need for supplemental fertilizers during peak growing season (Costa et al., 2011).

Table III.4 Amount of Total Nitrogen and Total Phosphorus supplied by the Treated Wastewater (ApR) throughout the year in San Laurenzo Golf Course.

	ApR -Quinta do Lago				
Reference year 2024	**Total N ApR m3**	**ApR N-Total mg/l**	**Total N kg/Golf Course**	**ApR P-Total mg/l**	**Total P kg/Golf Course**
Jan	5337	13	69	1.9	10
Feb	5337	12	64	3.2	17
Mar	16604	11	183	4.5	75
Apr	16604	0	0	4.3	71
May	51234	10	512	4.2	215
Jun	51234	18	922	7	359
Jul	51234	9	461	4.1	210
Aug	51234	31	1588	3.1	159
Sep	51234	13	666	1.9	97
Oct	16604	4	66	1.1	18
Nov	5337	6	32	2.1	11
Dec	5337	3.4	18	1.3	7
	327328		4583		1250
	Total Irrigated Area	**40ha**			

c) **Castro Marim**, annual wastewater reuse was **404,267 m³**, supplying **2,901 kg/year N** and **906 kg/ year P**. This corresponds to **97 kg N/ha/year** and **30 kg P/ha/year** across 30 hectares. Here, wastewater provides substantial Phosphorus coverage (close to full substitution) and about **40–50% of Nitrogen needs**. However, nutrient supply fluctuates strongly—e.g., Nitrogen availability was nearly zero in February–March but peaked at **949 kg N in July**. This variability requires careful nutrient scheduling to avoid seasonal shortage or surpluses.

Table III.5 Amount of Total Nitrogen and Total Phosphorus supplied by the Treated Wastewater (ApR) throughout the year in Castro Marim Golf Course.

	ApR -V.R.Sto António				
Reference year 2024	**Total N ApR m^3**	**ApR N-Total mg/l**	**Total N kg/Golf Course**	**ApR P-Total mg/l**	**Total P kg/Golf Course**
Jan	6591	13	86	2.2	15
Feb	6591	0	0	0	0
Mar	20506	0	0	0	0
Apr	20506	5	103	1.5	31
May	63277	4.3	272	1	63
Jun	63277	5	316	3.5	221
Jul	63277	15	949	3.7	234
Aug	63277	6	380	2.3	146
Sep	63277	5	316	1.4	89
Oct	20506	15	308	3.7	76
Nov	6591	20	132	3.8	25
Dec	6591	6	40	1	7
	404267		2901		906
	Total Irrigated Area	**30ha**			

d) **Quinta do Vale** received **268,229 m^3 of ApR annually**, contributing **1,925 kg/year N** and **601kg/year P**, or **51 kg N/ha/year** and **16 kg P/ha/year** over 38 hectares. This equates to covering **20–30% of Nitrogen** and **40–50% of phosphorus** requirements.

Similar to Castro Marim, nutrient availability was uneven, with high inputs during summer but negligible contributions in winter, requiring supplemental synthetic fertilization.

Table III.6 Amount of Total Nitrogen and Total Phosphorus supplied by the Treated Wastewater (ApR) throughout the year in Quinta Do Vale Golf Course.

	ApR -V.R.Sto António				
Reference year 2024	**Total N ApR m^3**	**ApR N-Total mg/l**	**Total N kg/Golf Course**	**ApR P-Total mg/l**	**Total P kg/Golf Course**
Jan	4373	13	57	2.2	10
Feb	4373	0	0	0	0
Mar	13606	0	0	0	0
Apr	13606	5	68	1.5	20
May	41984	4.3	181	1	42
Jun	41984	5	210	3.5	147
Jul	41984	15	630	3.7	155
Aug	41984	6	252	2.3	97
Sep	41984	5	210	1.4	59
Oct	13606	15	204	3.7	50
Nov	4373	20	87	3.8	17
Dec	4373	6	26	1	4
	268229		1925		601
	Total Irrigated Area	**38ha**			

III.4. Reduction of Carbon Emissions with Treated Wastewater Irrigation

Synthetic fertilizers are a extensively used tool in modern agriculture to increase crop production. Since their introduction in the early 20th century, agricultural yields have grown exponentially, enabling many regions to overcome historical problems such as hunger. However, their environmental impact has generated intense debate among scientists, and one of the less visible but most concerning aspects of their use is their significant contribution to our carbon footprint.

To understand how synthetic fertilizers affect greenhouse gas (GHG) emissions, it is important to examine their production and application. These products, also known as chemical fertilizers, are primarily synthesized using the Haber-Bosch process, which fixes atmospheric Nitrogen into ammonia. This process consumes large amounts of fossil energy, particularly natural gas, and releases substantial amounts of carbon dioxide (CO_2) during production (Paranychianakis et al., 2015; Moreira da Silva et al., 2020). Beyond this industrial footprint, once applied to soils, Nitrogen fertilizers contribute to nitrous oxide (N_2O) emissions, a greenhouse gas nearly 300 times more potent than CO_2 in terms of global warming potential. Significant portion of applied Nitrogen is not taken up by plants and is instead transformed by soil microbes through denitrification, releasing N_2O into the atmosphere (Moreira da Silva et al., 2020). Thus, reducing synthetic fertilizer use is not only a matter of resource efficiency but also of climate change mitigation.

The substitution of synthetic fertilizers with nutrients contained in treated wastewater (ApR) represents an important co-benefit of reuse, as it reduces both the consumption of industrial fertilizers and the associated greenhouse gas (GHG) emissions from their production and application. **Table III.7**. summarizes the amounts of Nitrogen (N) and Phosphorus (P) requirements, the amounts of N and P applied with the use of ApR and the carbon dioxide emissions equivalents (CO_{2e}) avoidance achieved in the four case study golf courses.

The carbon emissions (CE) related to the different amounts of synthetic fertilizers requirements in both irrigation conditions were quantified using the carbon footprint (CFP) of N- and P-fertilizer production in Europe at plant gate, calculated according to ISO 14067 (N-fertilizer CFP = 1.14 kg CO_2e/kg and P-fertilizer CFP = 0.71 kg CO_2e/kg). The CE related to the transportation of fertilizers was not considered in these calculations (Moreira da Silva et al., 2020).

The results show that all four courses achieved measurable reductions in fertilizer-related carbon emissions, although the quantity varied according to wastewater nutrient content and the irrigated area of each golf course:

a) **Salgados (56 ha)**: The Treated Wastewater (ApR) supplied 1,522 kg N/yr and 107 kg P/yr, reducing the need for equivalent amounts of synthetic fertilizer requirements. This avoided approximately 1.8 t CO_2e/yr. However, to maintain conventional nutrient application rates, an additional 8,898 kg N/yr and 2,763 kg P/yr would still be required.

b) **San Lorenzo (40 ha)**: The Treated Wastewater (ApR) provided 4,583 kg N/yr and 1,250 kg P/yr, corresponding to an avoidance of 6.1 t CO_2e/yr, the highest among the four courses. The remaining synthetic demand amounted to 2,877 kg N/yr and 820 kg P/yr.

c) **Castro Marim (30 ha)**: With 2,901 kg N/yr and 906 kg P/yr supplied by Treated Wastewater (ApR), avoided emissions reached 3.9 t CO_2e/yr. The course would still need approximately 2,739 kg N/yr and 699 kg P/yr of synthetic fertilizer.

d) **Quinta do Vale (38 ha)**: Treated Wastewater (ApR), provided 1,925 kg N/yr and 601 kg P/yr, corresponding to avoided emissions of 2.6 t CO_2e/yr. Nonetheless, the course would still require 5,195 kg N/yr and 1,404 kg P/yr in synthetic fertilizers requirements to reach conventional totals.

Taken together, the use of ApR across the four courses avoided 14.5 t CO_2e/yr of emissions associated with synthetic fertilizer production. Although this represents only a fraction of the total fertilization demand, it demonstrates the potential of ApR to contribute meaningfully to climate change mitigation. Importantly, the results show that avoided emissions are not strictly proportional to irrigated area but depend strongly on the nutrient content of the effluent supplied by each wastewater treatment plant (WWTP). These findings are consistent with Moreira da Silva et al. (2020), who reported that fertilizer substitution through ApR reuse in citrus orchards in the Algarve reduced carbon emissions by 23–27 kg CO_2e/ha/yr. In golf courses, the avoided emissions were considerably higher (ranging from 47 to 161 kg

CO_2e/ha/yr), reflecting the more intensive fertilization practices required for turfgrass maintenance.

TABLE III.7- Amount of avoided Carbon Emission related to the use of ApR

	N-Fertilizer (kg/yr)		**P-Fertilizer (kg/yr)**		**Avoided Carbon Emissions (t CO_2e /yr)**
Golf Course	**with ApR**	**N fertilizer requirement**	**with ApR**	**P fertilizer requirement**	**N,P-ApR use**
Salgados (Irrigat. 56ha)	1522	10420	107	2870	1.8
San Lorenzo (Irrigat. 40 ha)	4583	7460	1250	2070	6.1
Castro Marim (Irrigat 30 ha)	2901	5640	906	1605	3.9
Quinta do Vale (Irrigat. 38 ha)	1925	7120	601	2005	2.6

CF (Moreira da Silva *et al.*, 2020) **Total = 14.5 t CO_2 eq**

N-fertilizer = 1.14 kg CO_2 eq

P-fertilizer =0.7 kg CO_2 eq

II.5 Cost Comparison of the Use of ApR and of Water from Natural Sources

The comparative analysis of irrigation costs across the four case study golf courses reveals substantial variation in both the financial burden of water supply and the role of reclaimed wastewater (ApR) in mitigating reliance on natural sources. **Table III.8** compares the annual costs of using reclaimed wastewater (ApR) and natural water across four case study golf courses in the Algarve. The results show notable variation among the courses, reflecting differences in supply volumes, pricing structures, and arrangements with water providers.

a) **Salgados (56 ha)**, ApR use reached 400,000 m^3/yr during the study period, although cost data for ApR were not available. The course consumed 294,801 m^3/yr of natural water with no data cost. Without ApR cost data, a direct comparison cannot be made;

however, the high reliance on ApR indicates its importance in supplementing natural water sources, particularly in a condition of recurring water scarcity.

b) **San Lorenzo (40 ha)**, According to the management, ApR has been used consistently for over 20 years, making the course one of the earliest adopters of wastewater reuse for irrigation in the Algarve. Crucially, during this entire period the course has received ApR free of charge, which significantly reduced its overall irrigation expenditure compared to natural water. Natural water consumption amounted to 327,328 m³/yr, with no data cost. Following the rehabilitation of the Quinta do Lago WWTP, however, a tariff of 0.21 €/m³ is expected to be applied. Based on projected consumption levels of 515,000–565,500 m³/yr, this would result in an annual ApR cost of 108,000–119,000 €. Although this represents a substantial increase relative to the historical zero-cost supply and is higher than past natural water expenditure, it provides security of supply, regulatory compliance (EU Regulation 2020/741), and reduces pressure on natural freshwater resources. This illustrates that in San Lorenzo the adoption of ApR is less about immediate cost savings and more about long-term sustainability and resource security.

c) **Castro Marim (30 ha)**, ApR use total 161,420 m³/yr, at a cost of 30,960 €/yr, compared with 404,267 m³/yr of natural water, which cost 54,819 €/yr. In this case, ApR provided a clear financial benefit, reducing annual irrigation expenditure by approximately 44%, in addition to the environmental advantages of wastewater reuse.

d) **Quinta do Vale (38 ha)**, where ApR consumption was 145,436 m³/yr, costing 27,895 €/yr, compared to 268,229 m³/yr of natural water, costing 36,372 €/yr. Here, ApR resulted in savings of roughly 8,500 €/yr, further demonstrating its economic competitiveness under favourable pricing conditions.

TABLE III.8- Cost comparison of the use of ApR and of Water from Natural sources.

Golf Course	Quantity of ApR supply /m^3/yr	ApR €/yr/m^3	Quantity of Natural Water supply /m^3 /yr	Natural Water €/m^3
Salgados	400,000	*No data*	294,801	*No data*
San Lorenzo	280,164	*Pridicted 0.21€/ m^3*	327,328	*No data*
Castro Marim	161,420	30,960	404,267	54,819
Quinta Do Vale	145,436	27,895	268,229	36,372

Data for calculation

Quinta do Vale and Castro Marim - Water from Natural Source (Odeleite Dam): 0.1356 €/m^3

Castro Marin and Quinta do Vale- ApR from V.R. Sto António WWTP: 0.1918 €/m

IV. FINAL CONSIDERATION

IV.1. Global Discussion

This dissertation set out to evaluate the environmental, economic, and operational implications of reusing treated urban wastewater (Água para Reutilização - ApR) for the irrigation of golf courses in the Algarve, a representative Mediterranean region in Europe facing severe water scarcity. The multi-faceted analysis of four case study courses (Salgados, San Lorenzo, Castro Marim, and Quinta do Vale) and their associated wastewater treatment plants (WWTP) reveals that ApR partially substitute and increasingly necessary alternative to natural freshwater abstraction, particularly in Mediterranean regions facing recurrent drought, declining aquifer recharge, and mounting competition between tourism, agriculture, and urban populations.

a) **Water Security and Resource Substitution**: The quantification of natural water use confirmed the pressure that golf courses place on conventional water resources, with annual consumption ranging from 240,000 to over 400,000 m^3/yr and per course, peaking dramatically during the summer months. This demand directly tallies with the peak tourism season and lowest natural water availability, creating a critical stress point. The analysis of ApR availability showed that it can reliably meet a significant portion of this demand. For instance, the Albufeira Poente WWTP can fully supply Salgados year-round covers 100%, while other plants like Quinta do Lago WWTP (San Lorenzo) and Vila Real de Santo António WWTP (Castro Marim and Quinta do Vale**)** can cover 40-90% of summer demand for their respective courses. This replacement directly conserves precious freshwater reserves (surface and groundwater) for higher priority uses like public supply and ecological flows, enhancing groundwater recharge and regional water security.
b) **Nutrient Recycling and Fertilizer Reduction**: In this study ApR plays vital role for nutrient recycling. The nutrient content (N and P) in the treated effluent varied significantly between WWTP, leading to different levels of synthetic fertilizer

substitution. **Salgados Golf Course,** supplied by Albufeira Poente WWTP, achieved more modest benefits, with ApR contributing approximately 10–15% of Nitrogen and less than 10% of Phosphorus needs**. San Lorenzo Golf Course**, supplied by the Quinta do Lago WWTP, demonstrated the highest potential, effectively meeting 50-70% of Nitrogen and nearly all Phosphorus needs. **Castro Marim Golf Course** and **Quinta do Vale Golf Course,** both supplied by Vila Real de Santo António WWTP, benefitted from effluent with high Phosphorus content, covering close to full Phosphorus substitution respectively and supplying about 40–50% and 20–30% of Nitrogen requirements. This transforms wastewater from a waste product into a valuable fertilizer source, closing the nutrient loop and decreasing the cost related to synthetic fertilizers.

c) **Carbon Emission Mitigation:** The reduction in synthetic fertilizer use directly translates into a reduction in the carbon footprint of golf course maintenance. By avoiding the energy-intensive production of fertilizers (Haber-Bosch process for N) (Huygens et al., 2020), the four courses collectively avoided an estimated **14.5 t of CO_2e annually**. This underscores that water reuse is not only a water conservation strategy but also a climate action protection measure. The variability in avoided emissions (from 1.8 to 6.1 t CO_2e *per* course) highlights, again, the importance of effluent nutrient concentration.

The number of golf rounds can be an indicator for the functioning of golf courses. The carbon emission related to each round can be an indicator for the environmental performance of each golf course. In 2024, the studied golf courses had the number of rounds showed in the **Table IV.1**. In this table it is shown that the CO_2 emissions avoidance increase with the increase of the nutrient content of the ApR. However, golf rounds sustainability (Avoided Carbon Emissions g/rounds) decreases with the increase of the number of rounds per year – so, increasing the playability pressure, decreases the avoidance of CO_2 emission per number of rounds.

TABLE IV.1: Golf rounds and avoid carbon emissions using ApR

2024(CNIG,2025)	**Golf Courses**	**Number of Rounds per yr**	**Avoided Carbon Emissions (kg CO_2e)**	**Avoided Carbon Emissions (g CO_2/rounds)**
	Salgados	47,393	1810	38
	San Lorenzo	52,000	6100	12
	Castro Marim	19,970	3941	198
	Quinta do Vale	23,578	2615	111

d) **Economic Viability:** The cost-benefit of ApR is highly sensitive to local tariff structures. In **Castro Marim** and **Quinta do Vale**, where ApR is priced competitively (€0.19/m³), it provides direct financial savings compared to natural water. In San Lorenzo is particularly instructive: two decades of free ApR use provided massive economic advantage, but the introduction of a modern tariff (€0.21/m³) following infrastructure upgrades will increase future costs. ApR is moving from a low-value by-product to a managed, high-quality resource, and its pricing must reflect the investment in treatment infrastructures and distribution while remaining attractive to end-users.

For all the reasons the use of ApR in golf irrigation seems to be a feasible solution to face water scarcity in Algarve region. In the next year, tourism will continue to be of most importance to Portuguese economy, and the golf is the most profitable activity related to tourism mainly in coastal areas. To have a sustainable golf industry we will need to incorporate the best environmental practices as the use of ApR.

These study needs to continue and include more aspects related to, for instance, soil and plant analyses, energy alternatives (solar, eolic), water alternatives (such as dessalinisation), the use of ApR more adaptaded turfgrass species and the introduction of new technologies related to the management of turfgrass irrigation, such as AI, data science and IoT.

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