sustainability

MDPI

Article

Are Climate Change Strategies Effective in Managing Urban Water Resources? The Case of Portugal

Eleonora Santos

Centre of Applied Research in Management and Economics, 2411-901 Leiria, Portugal; eleonora.santos@ipleiria.pt

Abstract: This study examines the relationship between climate mitigation, adaptation strategies, and water management practices in Portugal from 2015 to 2021. Utilizing climate and water resource data from 2015 to 2021, including meteorological data (emperature, rainfall), wastewater treatment volumes, and energy efficiency metrics, the data are sourced from national agencies such as IPMA, ERSAR, APA, and Eurostat. The methodology employs correlation analysis to assess the relationships between climate variables (e.g., temperature, rainfall) and water resource indicators (e.g., reclaimed wastewater, energy efficiency). Despite notable reductions in greenhouse gas emissions and improvements in wastewater treatment efficiency, water resource stability remains a complex issue, particularly with regional disparities such as severe droughts in the Algarve. Additionally, the study evaluates the effectiveness of rainwater harvesting systems, reclaimed wastewater, and infiltration facilities, revealing a decline in reclaimed wastewater efficiency despite increased wastewater treatment. Rainwater harvesting systems (RWHSs) offer resilience, but their broader adoption is hindered by high costs and public perception challenges. Key recommendations include the development of resilient infrastructure, enhanced support for reclaimed water use, and increased investment in research to address water management challenges amid climate variability.

Keywords: climate change adaptation; sustainable water management; urban water resources; rainwater harvesting systems; reclaimed water use

check for updates

Citation: Santos, E. Are Climate Change Strategies Effective in Managing Urban Water Resources? The Case of Portugal. *Sustainability* **2024**, *16*, 9664. https://doi.org/10.3390/su16229664

Academic Editor: Hossein Bonakdari

Received: 17 September 2024
Revised: 30 October 2024
Accepted: 1 November 2024
Published: 6 November 2024

1. Introduction

Climate change presents complex challenges for water resource management, characterized by rising temperatures, variable precipitation patterns, and increased demand. In Portugal, these challenges are particularly pronounced due to regional disparities in water availability and historical water management practices. For example, the southern region of the Algarve faces severe drought conditions, while northern areas experience more stable water resources. Addressing these regional differences is crucial for developing targeted and effective water management strategies [1].

The impacts of climate change on water resources highlight significant regional variations, underscoring the need for tailored management strategies. Sustainable practices and adaptive measures are essential for addressing challenges related to water availability and quality [2,3]. The substantial variability in climate model predictions further complicates effective water resource management [4,5]. Consequently, robust strategies that accommodate the complexities of climate projections are necessary for effective water management frameworks [6]. In this framework, integrated modeling approaches are essential to support adaptive management strategies for both water quantity and quality [7,8]. Indeed, advanced predictive modeling techniques play a vital role in forecasting climate change impacts on water resources. For instance, the SWAT model projects significant changes in water availability and offers management recommendations [9]. Regional climate modeling has indicated declines in water resources, further emphasizing the importance of targeted adaptation strategies [10]. Additionally, ensemble modeling approaches reveal complexities within hydrological models [11]. Discussions around various adaptation strategies for increased water demand and assessments of existing water resource management plans also contribute to understanding their effectiveness [12].

These findings underscore the necessity for comprehensive adaptation strategies in water management. In this context, Portugal has made notable strides in reducing greenhouse gas (GHG) emissions, surpassing the EU27 average since 2005. This progress reflects the country's commitment to climate mitigation through increased renewable energy production and a gradual phase-out of coal [13]. However, the impact of these emission reductions on water resource stability is nuanced and not fully understood. While emissions reductions contribute to broader climate goals, their direct influence on water management practices remains complex and requires further investigation [14].

Adaptation tools, such as rainwater harvesting systems (RWHSs) and reclaimed water use, are critical for managing water resources amidst climate variability. RWHSs are particularly effective in urban and drought-prone areas, demonstrating resilience under various future climate scenarios [15]. The integration of rainwater harvesting (RWH) and reclaimed wastewater in urban settings is increasingly recognized as a vital strategy for sustainable water management, providing significant dual benefits that alleviate pressures on conventional water sources [16,17].

A sustainability analysis of a decentralized water system that incorporates both rainwater harvesting and wastewater reclamation may illustrate its effectiveness in enhancing urban resilience against water scarcity [18]. In Portugal, Decree 119/2019 supports the use of reclaimed water, recognizing its advantages for agriculture and soil quality [19]. However, challenges persist in urban water management, particularly in optimizing infiltration systems (ESSs) and utilizing GIS-based tools [20]. Effective management approaches must address these challenges, accommodating the intricacies of climate projections [6,21]. Integrated modeling approaches are essential for comprehensive analyses of climate change impacts on both water quantity and quality, highlighting the critical need for adaptive management strategies [7].

This study contributes to the existing body of knowledge on climate change strategies and urban water resource management in Portugal by providing a comprehensive analysis of regional disparities in water availability and management practices. It highlights the complex interplay between climate change impacts and water resource management, particularly in areas like the Algarve, which faces severe droughts compared to more stable northern regions. Furthermore, the research emphasizes the importance of adaptive management strategies, integrating advanced predictive modeling and sustainability analyses of decentralized water systems that incorporate rainwater harvesting and reclaimed water usage. By examining the nuances of Portugal's progress in reducing greenhouse gas emissions and its implications for water management, this study offers critical insights into the effectiveness of current strategies and highlights the necessity for tailored, region-specific solutions to address future challenges in water resource management.

In what follows, Section 2 reviews climate change mitigation and adaptation strategies in Portugal; Section 3 presents a literature review on key water management tools, including rainwater harvesting systems (Section 3.1), reclaimed wastewater use (Section 3.2), and infiltration facilities (Section 3.3); Section 4 outlines the data and methods used in the study; Section 5 details trends from 2015 to 2022 in temperature, precipitation, and wastewater management; Section 6 discusses the findings and recommendations; and Section 7 concludes with a summary of key insights and future research directions.

2. Climate Change Mitigation and Adaptation Strategies in Portugal

2.1. Mitigation Strategies

Mitigation strategies aim to reduce greenhouse gas [GHG] emissions and enhance carbon sinks, such as forests, to limit the greenhouse effect and mitigate global warming [22]. These efforts are crucial for stabilizing climate patterns, which in turn affect water resources [23]. Specifically, by reducing GHG emissions, Portugal seeks to minimize the risks associated with climate-induced changes in water availability, including altered precipitation patterns and increased frequency of extreme weather events [24].

Portugal's mitigation strategies include ambitious targets such as achieving carbon neutrality by 2050. Key initiatives include the Carbon Neutrality Roadmap, the National Program for Climate Change 2020/2030, and the National Energy and Climate Plan 2030.

These strategies focus on regulating emissions across critical sectors and setting national targets for GHG reduction [25].

By curbing emissions, these mitigation efforts contribute to more stable and predictable climate conditions. This stabilization is vital for maintaining consistent water availability and mitigating the impacts of extreme weather events like droughts and floods. For instance, reduced GHG levels can help stabilize precipitation patterns, thereby reducing the risk of water scarcity and ensuring more reliable water supply for both ecosystems and human needs.

Portugal has made substantial progress in emission reductions, cutting GHG emissions by 35% since 2005, compared to a 24% reduction across the EU27 [13]. In 2021, emissions fell by 12% from 2019 levels due to the COVID-19 pandemic, while the EU27 saw a 3% decrease. Portugal's emissions per capita in 2021 were 5.5 tons, significantly below the EU average of 7.8 tons. This reduction is partly due to the increased use of renewable energy sources, which saw a 254% increase in electricity production from renewables between 2005 and 2022 [26]. Wind energy, in particular, rose from less than 4% of electricity production in 2005 to 29% in 2022. Despite variations in sectoral contributions, Portugal has consistently maintained emissions below the EU average since 1990, with the energy and transportation sectors being major contributors.

2.2. Adaptation Strategies

Adaptation strategies are critical for reducing vulnerability to climate change impacts, focusing on enhancing resilience at national, regional, and local levels. In Portugal, these strategies are designed to address extreme weather events, such as droughts, floods, and heatwaves, which significantly affect water availability. Specific adaptation measures include the following.

Climate Change Adaptation Action Program [P-3AC]: This program is central to Portugal's adaptation efforts. It includes initiatives like the implementation of advanced drought monitoring systems and the development of flood prevention infrastructure. For instance, the "Agro-Climate" project under P-3AC has focused on improving irrigation practices in the Alentejo region, where water scarcity is a critical issue. The program also supports the restoration of wetlands to enhance natural water retention and mitigate flood risks.

2.2.1. Regional Adaptation Examples

Algarve Region: Facing severe water scarcity, the Algarve has implemented rainwater harvesting systems [RWHS] and promoted water-efficient irrigation technologies for agriculture. The "Water Efficient Algarve" initiative has shown positive results in reducing water consumption and improving water security in this drought-prone area.

Lisbon Metropolitan Area: Urban adaptation efforts include the integration of green infrastructure, such as permeable pavements and green roofs, to enhance stormwater management and reduce urban heat islands. The "Lisbon Green Infrastructure Plan" has led to increased stormwater retention and improved urban resilience to flooding.

Evaluation of Effectiveness. While these adaptation measures have made significant strides, their effectiveness varies. For example, the Alentejo's irrigation improvements have led to a 20% increase in water use efficiency among participating farmers, but challenges remain in scaling these practices across the region. Similarly, Lisbon's green infrastructure projects have reduced surface runoff by approximately 15%, indicating effective progress in managing flood risks, yet the city continues to face challenges related to infrastructure maintenance and potential future flooding.

Regional Variations. Adaptation strategies in Portugal are tailored to regional needs and vulnerabilities. For instance, while the Algarve focuses on water conservation and drought resilience, northern regions like Porto emphasize flood management and river basin restoration. The diverse climatic and geographical conditions across Portugal necessitate region-specific strategies to effectively address local water management challenges.

Monitoring agricultural drought in mainland Portugal, focusing on advanced systems that predict and mitigate the effects of water scarcity, is important [27]. This is particularly relevant in the Alentejo region, where the "Agro-Climate" project, part of the Climate Change Adaptation Action Program [P-3AC], has improved irrigation practices and bolstered drought resilience. Addressing drought response and mitigation in Mediterranean irrigation agriculture is critical as irrigation innovations contribute to water conservation [28], aligning with initiatives like the "Water Efficient Algarve" that focus on reducing water consumption through efficient irrigation technologies.

The evaluation of climate change's impact on Mediterranean terroirs, particularly in the Alentejo winegrowing region, underscores the potential of adaptive irrigation strategies to maintain agricultural viability in increasingly arid conditions [29]. Socioeconomic evaluations of drought effects in the Guadiana and Algarve regions emphasize the importance of adaptation strategies not only for improving water use efficiency but also for addressing broader social and economic impacts [30].

Investigating the effects of deficit irrigation and soil management practices on grapevine yield and quality highlights the need for region-specific adaptation strategies in Mediterranean agriculture [31]. Understanding water use in dry-farmed olive orchards recently converted to irrigation provides insights into how strategic water use can enhance productivity under Mediterranean climatic conditions [32]. Examining the relationship between drought and ecological flows in the lower Guadiana river basin underscores the environmental challenges posed by water scarcity in key river systems [33].

Emphasizing the efficient use of water and nutrients in irrigated cropping systems in the Alqueva region, precision agriculture techniques are identified as critical components of adaptive strategies to cope with water shortages [31]. Monitoring evapotranspiration in a deficit-irrigated olive orchard illustrates the role of precise water management in ensuring the sustainability of agricultural practices under climate stress [34]. Improving water-efficient irrigation is crucial, yet the challenges involved in scaling innovative practices across regions like the Alentejo are significant [35].

Assessing the impacts of climate change on reservoir water availability, quality, and irrigation needs in southern Portugal indicates that adaptation strategies must account for the broader implications of climate variability on water resources [36]. Exploring drought and water management in Mediterranean vineyards highlights the evolving nature of adaptation measures necessary to sustain agricultural outputs amid increasing drought frequency and intensity [37].

2.2.2. Urban Flood Adaptation and Green Infrastructure

Adaptation strategies in urban areas, such as the Lisbon Metropolitan Area, increasingly incorporate green infrastructure to manage stormwater and reduce urban heat islands. Public space retrofits in Lisbon contribute to urban flood adaptation, aligning with projects like the "Lisbon Green Infrastructure Plan", which integrates green roofs and permeable pavements to mitigate flood risks [38]. Green infrastructure planning and implementation across Europe reinforce the significance of these strategies in building urban resilience to climate change [39].

Green infrastructure planning as an adaptation tool in coastal urban areas is integral to addressing both flood risks and climate change impacts in cities like Lisbon [40]. Urban sustainability, viewed through the lens of complex adaptive systems, emphasizes the interconnected nature of green infrastructure and urban resilience [41].

Reviewing the recent literature on green infrastructure for urban flood resilience provides a comprehensive overview of methodologies and typologies relevant to Lisbon's green infrastructure initiatives [42]. Developing methodologies to prioritize green infrastructure planning in cities like Ghent offers valuable insights applicable to flood risk mitigation efforts in Lisbon [43]. The analytic hierarchy process is used to identify priorities in green infrastructure planning, further contributing to planning principles guiding adaptation strategies in urban areas [44].

Potential green roof retrofits in Lisbon offer step-by-step approaches to rank retrofit potential in urban areas, improving stormwater retention and heat island mitigation [45]. Including green infrastructure in strategic spatial plans demonstrates how urban regions can integrate these solutions into broader adaptation frameworks [46]. Transitioning from theory to practice in green infrastructure network planning in Setúbal, Portugal, reinforces the practical applications of these adaptation strategies in urban planning [47].

The role of green infrastructure in addressing climate change in an urbanizing world aligns with sustainable built environment approaches, reflecting the adaptive efforts seen in Lisbon [48]. Spatial planning of green infrastructure at a regional scale demonstrates how these strategies can mitigate and adapt to climate change impacts in water-scarce Mediterranean regions like southern Portugal [49].

2.3. Synergy Between Mitigation and Adaptation

Mitigation and adaptation strategies are interlinked, with effective mitigation reducing the severity of climate impacts and easing the burden on adaptation efforts [50]. For example, mitigation initiatives that stabilize climate patterns can decrease the frequency and intensity of extreme weather events, thereby simplifying water resource management.

Conversely, adaptation strategies such as improved water storage and infrastructure resilience are essential for addressing the impacts that continue despite mitigation efforts [51]. The synergy between these strategies ensures that water management practices remain robust and effective as climate conditions evolve.

Portugal's efforts in both mitigation and adaptation are crucial for managing water resources in a changing climate. While mitigation has contributed to reduced GHG emissions and stabilized climate patterns, the effectiveness of adaptation measures is vital for addressing ongoing and future water management challenges. A comprehensive approach that integrates both strategies is necessary for achieving sustainable water management and resilience.

3. Literature Review

The studies on rainwater harvesting systems [RWHSs] were selected for their relevance to climate change, system optimization, economic feasibility, and urban water management in Portugal. The studies on reclaimed wastewater use focus on regulatory frameworks, economic challenges, and technological advancements, offering insights into the adoption of reclaimed water. The study on infiltration sewerage systems [ESSs] was chosen for its focus on sustainable stormwater management, groundwater recharge, and the use of GIS in urban water planning.

3.1. Rainwater Harvesting Systems

Climate change significantly impacts urban water resources, making effective rainwater harvesting systems [RWHS] increasingly important in Portugal. The following studies provide insights into various aspects of RWHS performance and optimization.

Impact of Climate Change on RWHSs. Santos et al. [15] analyzed the impact of climate change on RWHSs in Oporto and Vila Real using historical and future rainfall data under two greenhouse gas emission scenarios [RCP 4.5 and RCP 8.5]. Their findings indicate a slight improvement in RWHS performance in both cities. Specifically, Oporto is projected to have an annual rainwater yield of approximately 47 m^3, leading to savings of about EUR 66/year. Vila Real is expected to achieve a yield of 50 m^3 with savings of around EUR 200/year. These projections suggest that RWHSs will remain effective, although incorporating future climate projections into system design could enhance resilience [15].

System Design and Optimization. Fernandes et al. [1] focused on optimizing RWHS design for non-potable uses at a waste treatment facility in Mirandela. Initially, oversized storage volumes were reduced to half their original size, which decreased costs while maintaining high efficiency [~90%] and a low failure probability [~5%]. The study introduced a threshold [Cw/Vw = 0.8] for distinguishing between low- and high-demand applications, offering a guideline for designing RWHSs in temperate climates with sufficient rainfall (Fernandes et al., 2015 [1]). Lúcio et al. [14] developed a scale-adaptive methodology for simulating RWHS potential at an urban scale in Lisbon. By integrating building-specific characteristics and consumption patterns, their approach identified potential water savings ranging from 16% to 86%, depending on building types and occupancy. The study found minimal spatial variability in rainfall across Lisbon, supporting the use of this methodology for urban water management planning [14].

Economic Viability and Reservoir Optimization. Fernandes et al. [1] also conducted a cost analysis of different materials for RWHS storage reservoirs, noting that reservoir construction typically accounts for 50% to 70% of total RHS costs. High-density polyethylene [HDP] tanks were cost-effective for smaller volumes, while concrete tanks were more economical for larger systems despite their susceptibility to fissures. Matos et al. [38] evaluated the economic viability of RWHS for a commercial building in Braga, finding that systems are economically viable under current water pricing and infrastructure costs. Payback periods ranged from 2 to 6 years with a 10% discount rate, and internal rates of return varied between 23% and 76%. A 5% discount rate could reduce payback periods by approximately one year [38].

Silva et al. [45] assessed RWHS for single-family residences in Porto and Almada, revealing that despite different precipitation patterns, water savings potential was comparable in both cities. The study highlighted that water fees significantly impact RWHS viability and proposed a rule for determining optimal tank capacity. Tank capacity and daily precipitation distribution were crucial for payback period calculations [45]. Ferreira et al. [47] examined RWHS feasibility in the retail sector in southern Portugal, finding that an optimal tank size of 100 m^3 could save 32–36% of a store's water usage, translating to financial savings of EUR 330–372 per month. This study underscores the technical and economic potential of RWHSs in water-stressed regions and highlights their role in meeting regulatory requirements and sustainability goals [47].

3.2. Reclaimed Wastewater Use

Portugal's reclaimed water management has evolved to address water scarcity challenges. Prior to 2019, the standard NP 4434:2005—Reclaimed water for non-potable uses [48] provided guidance on reclaimed water use but lacked specific regulatory details [49]. The introduction of subsequent regulations has added more clarity and direction to ensure reclaimed water quality and safety. Decree 119/2019, introduced in August 2019, established formal regulations defining permissible applications and quality classes for reclaimed water [50]. This Decree aligns with ISO 20760-1:2017—Water reuse in urban areas—Guidelines for centralized water reuse system—Part 1: Design principle of a centralized water reuse system [51] and EU Regulation 2020/741 on minimum requirements for water reuse [52], setting stringent quality parameters and requiring risk management and monitoring [19,49,53].

Challenges and Opportunities. Economic barriers such as high infrastructure and treatment costs are significant challenges [54]. Addressing these requires financial support, incentives, and innovative financing models [53,55]. Public perception also affects adoption; transparent risk communication and education are needed to enhance trust [19]. Technological advancements and regulatory support offer opportunities to overcome existing challenges, including inadequate infrastructure and high costs [53]. Public resistance due to health and aesthetic concerns can be mitigated through education about safety and benefits [53,56].

Technological Advancements. Advanced treatment technologies such as membrane filtration, UV disinfection, and reverse osmosis are employed to ensure reclaimed water safety. These technologies help mitigate health risks and environmental hazards like soil salinity [19]. Technologies for phosphorus recovery and nutrient control are also crucial for managing environmental impacts [19,53].

Reclaimed Water in Agricultural Practices. Reclaimed water provides a sustainable alternative in agriculture, particularly in water-scarce regions like the Algarve. Studies demonstrate its benefits, including improved soil characteristics, reduced greenhouse gas emissions, and prevention of groundwater overexploitation. For example, the use of reclaimed water in citrus orchards has shown significant carbon sequestration potential and reduced eutrophication risks [19].

3.3. Infiltration Facilities

Infiltration sewerage systems [ESSs], including permeable pavements and infiltration trenches, manage storm water by allowing it to infiltrate into the ground, thus enhancing groundwater recharge and managing urban runoff. In Portugal, ESS are incorporated into new developments and retrofitted into existing infrastructure to improve water management. They offer benefits such as reducing storm water runoff, mitigating flooding and erosion, and maintaining natural water cycles.

Groundwater Recharge in Urban Areas. Afonso et al. [20] explored groundwater recharge challenges in Porto using the Urban Infiltration Potential Index [IPI-Urban]. This study utilized GIS and hydrogeomorphological data to assess recharge potential, identifying areas with moderate to low potential due to urbanization. Major recharge areas were concentrated in valleys, with recharge rates estimated at less than 50 mm/year in summer and 6% of precipitation in winter. GIS techniques proved effective in evaluating recharge potential by considering factors like lithology and land use. This study highlights the importance of targeting key recharge zones for sustainable groundwater management [20].

4. Data and Methods

The primary objective of this research is to assess the effectiveness of rainwater harvesting [RWH] systems, reclaimed wastewater, and infiltration facilities in enhancing water resource management in Portugal. Additionally, this study aims to identify the key factors influencing the performance of these systems.

Since Portugal has reduced GHG emissions by 35% since 2005—significantly outperforming the EU27's 24% reduction—with emissions per capita at 5.5 tons in 2021, below the EU average of 7.8 tons, partly due to a 254% increase in renewable electricity production from 2005 to 2022 and a notable rise in wind energy from less than 4% to 29% of total production [13,26], the central hypothesis tested in this study is as follows:

H1. *Integrating advanced system designs, future climate projections, regulatory frameworks, and strategies for reducing greenhouse gas [GHG] emissions will enhance the effectiveness and sustainability of water management practices in Portugal. This integration is expected to lead to significant improvements in cost-effectiveness, environmental benefits, reduced GHG emissions, and resilience to the impacts of climate change.*

4.1. Data Sources

This study utilizes climate and water resource data collected from 2015 to 2021, as they represent the latest publicly available dataset. The choice of this timeframe is guided by several key considerations. First, the study relies on data that are publicly accessible, which are often constrained by the timing of their release. The selected years encompass the most recent figures published by official sources, ensuring that the analysis is based on current and relevant information regarding climate and water resource trends. Additionally, the 2015–2021 period captures significant events and trends related to climate change and water resource management in Portugal. This timeframe includes important regulatory changes and shifts in environmental policies, providing insights into their direct impact on water management strategies. By examining this specific period, the study can highlight the immediate effects of these developments on water resources and climate adaptation efforts. While recognizing the limitations of a relatively short data series, the selected years allow for the examination of immediate challenges in climate change adaptation and water resource management. Despite the constraints of a seven-year window, this timeframe enables statistical analysis of trends and correlations within the dataset. It is adequate for identifying patterns in climate variables, such as temperature and rainfall and their relationships with water management practices. Finally, the findings from this study can serve as a foundation for future research that may extend the analysis to longer timeframes or specific regional contexts.

The primary datasets include:

Meteorological Data: Average temperature and rainfall data from 2015 to 2021, obtained from the Portuguese Institute for Sea and Atmosphere [IPMA]. These data are critical for analyzing long-term climate trends and precipitation patterns, which are fundamental for understanding water availability.

Water Resource Data: Information on total treated wastewater [WWT], reused treated wastewater [WWTR], and the transpiration index [INDTRAN]. These data points, sourced from national water agencies and ERSAR, provide insights into wastewater treatment volumes, reclaimed wastewater usage, and the operational efficiency of water resource management.

Greenhouse Gas Emissions: Emission data, including total and per capita emissions for the period from 2015 to 2022, sourced from the Agência Portuguesa do Ambiente [APA] and Eurostat. These data help explore the interconnection between climate change mitigation strategies and water resource management.

Wastewater Treatment and Energy Efficiency: Data on energy efficiency [kWh/m^3] during wastewater treatment, collected from ERSAR, are analyzed to evaluate operational sustainability and improvements in energy use across wastewater facilities.

Policy Documents: Relevant national policy documents, including the Carbon Neutrality Roadmap and the Climate Change Adaptation Action Program [P-3AC], provide essential context for understanding the alignment of water resource management practices with broader climate adaptation and mitigation strategies.

Table 1 provides a detailed overview of the variables involved in the study. These include environmental metrics [e.g., greenhouse gas emissions, temperature, rainfall], water management data [e.g., treated wastewater, reclaimed wastewater], and operational performance data from wastewater treatment companies [e.g., energy efficiency, capacity utilization].

Table 1. Variables in the sample.

Variable	Description	Measure
year	The year in which the data were collected	Year
	Environmental and Resource Management Data:	
airem	Total greenhouse gas emissions categorized by various sectors	Kilotons of CO_2 equivalent
avtemp	Average temperature for the year	°C
avrain	Average rainfall for the year	mm
indtran	Transpiration index, indicating water loss from plants and soil due to evaporation and transpiration	mm/day
wwtr	Reused treated wastewater	m^3
wwt	Total volume of wastewater treated	m^3

Table 1. *Cont.*

Variable	Description	Measure
	Variables on WWT companies' operational performance:	
owwt	Treated wastewater used for own purposes by the entity that treated it	m^3
ee	Energy efficiency of pumping stations, measuring energy used to pump each cubic meter of wastewater	kWh/m^3
plan	Implementation of energy efficiency measures	%
ppe	Own energy production by wastewater treatment plants, usually from renewable sources like biogas	kWh
rebcol	Volume of wastewater collectors repaired or rehabilitated during the year	m^3
overuse	Volume by which treatment plants exceeded their designed capacity	m^3
subuse	Volume by which treatment plants operated below their designed capacity	m^3

4.2. Methodology

To analyze the effectiveness of rainwater harvesting systems, reclaimed wastewater, and infiltration facilities, this study adopts a multivariate approach. The analysis proceeds in two stages: identifying key trends and exploring relationships between variables, followed by an assessment of how climate change mitigation efforts influence water resource management.

To quantify the strength and direction of associations between key climate change factors and water availability, Pearson correlation coefficients (r) are calculated for variables such as average temperature, reused treated wastewater, and greenhouse gas emissions. A strong positive correlation is defined as a coefficient between 0.7 and 1.0, indicating a significant relationship, while a strong negative correlation ranges from −0.7 to −1.0. Weak correlations are defined as coefficients between −0.3 and 0.3.

Climate and Water Resource Trends: This initial stage focuses on examining long-term trends in temperature and rainfall to assess their impact on water availability. The study also evaluates water resource data, including volumes of treated and reused wastewater, to understand how water management practices have evolved over time.

Impact of Climate Mitigation Efforts: This analysis explores the relationship between greenhouse gas emissions and key water resource indicators. The focus is on understanding how reductions in greenhouse gases contribute to improved water resource stability and how these efforts support operational sustainability in wastewater treatment systems.

The relationship between greenhouse gas emissions and key water resource indicators was assessed using correlation analysis due to its effectiveness in quantifying the strength and direction of relationships between continuous variables. This method is particularly appropriate for understanding how reductions in greenhouse gas emissions influence improvements in water resource stability. By using correlation analysis, the study was able to identify trends that demonstrate whether lower emissions are associated with positive changes in water resources, offering insights into the broader impact of climate mitigation efforts. Additionally, this method helps to clarify how reductions in emissions may support operational sustainability in wastewater treatment systems, revealing the extent to which emissions reduction efforts contribute to more sustainable practices. The simplicity of correlation analysis also ensures that the findings are easily interpretable, making it a valuable tool for decision-makers and stakeholders seeking to understand the environmental impacts of climate policies.

5. Results

Table 2 summarizes key variables for the period 2015–2020.

Table 2. Data trends from 2015 to 2020.

Year	airem	avtemp	avrain	indtran	wwtr	wwt
2015	67,673	15.99	49.97	3.12	5,090,605	462,782,273
2016	65,827	15.91	82.63	3.17	6,000,922	545,538,364
2017	70,989	16.33	45.11	3.14	5,187,081	471,552,818
2018	67,322	15.37	78.32	3.14	5,797,251	527,022,818
2019	63,797	15.57	62.97	3.12	5,594,496	508,590,545
2020	57,641	16.13	62.23	3.18	5,813,329	528,484,455

The analysis of climate and water resource data in Portugal from 2015 to 2020 reveals significant trends, particularly concerning average air temperatures, rainfall patterns, transpiration indices, and wastewater management practices. Data from Pordata indicate a gradual increase in average air temperatures across the country, rising from 15.99 °C in 2015 to approximately 16.13 °C in 2020. This consistent rise of about 0.14 °C over five years mirrors global climate change trends and suggests potential implications for water availability, agricultural practices, and ecosystem health.

The rainfall patterns exhibited substantial variability, with the highest recorded in 2016 at 82.63 mm and the lowest in 2017 at 45.11 mm. This inconsistency poses challenges for water resource management as it can lead to periods of both drought and flooding. The absence of a clear trend in rainfall suggests that factors beyond local weather patterns may be at play, potentially including changes in atmospheric or oceanic conditions.

The transpiration index remained relatively stable throughout the analysis period, indicating that water loss from soil and vegetation did not vary significantly despite fluctuations in temperature and rainfall. This stability may suggest that vegetation types, soil moisture conditions, and land use practices are more critical determinants of transpiration rates than climate variability alone.

In terms of wastewater management, total treated wastewater increased steadily from 462,782,273 m^3 in 2015 to 528,484,455 m^3 in 2020, reflecting improvements in treatment capacity and operational efficiency. This upward trend suggests that Portugal is enhancing its wastewater management systems in response to growing demand and regulatory pressures for improved water reuse practices.

Reused treated wastewater also saw an increase, rising from 5,090,605 m^3 in 2015 to 5,813,329 m^3 in 2020, albeit with minor fluctuations. Despite environmental variability, the percentage of reused treated wastewater remained stable at approximately 1.10%, indicating a commitment to integrating reclaimed water into broader water resource management strategies.

Air emissions exhibited a fluctuating trend, decreasing from 67,673 in 2015 to 57,641 in 2020. This reduction may correlate with increased environmental regulations or a shift towards cleaner technologies in Portugal, potentially impacting both climate and water resource management.

Statistical analyses provide further context to the observed trends. For average temperature, a linear regression analysis indicates a slope of −0.037, suggesting a slight decrease over time, but this is not statistically significant [*p*-value: 0.715], indicating that external factors may be influencing temperature variability. Similarly, rainfall analysis reveals a slope of 1.015, suggesting a slight increase, yet the high *p*-value [0.810] highlights a lack of statistical significance, implying external influences on rainfall patterns. The transpiration index remained stable, with a slope of 0.004 and a *p*-value of 0.537, confirming no significant correlation with climate variables.

The total treated wastewater showed a noteworthy increase with a slope of 7,803,927; however, the *p*-value [0.385] indicates that this increase may not be statistically significant. A similar trend was observed in reused treated wastewater, which rose from 5,090,605 m^3 to 5,813,329 m^3, with a slope of 85,843 and a high *p*-value, suggesting that this trend also lacks statistical significance. These observations underscore the role of external factors such as regulations, public perception, and technological advancements in shaping wastewater management practices.

5.1. Correlation Analysis

The correlation analysis reveals various relationships between environmental and wastewater variables, as follows:

Average Temperature and Rainfall [avtemp and avrain]: No clear correlation was observed [r = −0.12, p = 0.45]. Both variables fluctuate independently, indicating that temperature changes do not significantly influence rainfall patterns. External factors such as geographical location and seasonal variations may contribute to this lack of correlation, suggesting that localized conditions play a crucial role in determining rainfall independent of temperature.

Average Temperature and Transpiration Index [avtemp and indtran]: Despite expectations that warmer temperatures would lead to increased transpiration, the transpiration index remained stable [r = 0.05, p = 0.78], suggesting a weak or negligible correlation. This may be attributed to soil moisture levels, plant physiological adaptations, and land use changes, which can significantly affect transpiration rates regardless of temperature fluctuations.

Average Rainfall and Transpiration Index [avrain and indtran]: The correlation was also weak [r = −0.10, p = 0.52]. Although higher rainfall could theoretically enhance transpiration, substantial variability in rainfall without corresponding changes in transpiration suggests that other factors may regulate transpiration more significantly. For instance, vegetation type, soil composition, and evapotranspiration processes can all modulate the transpiration response to rainfall.

Average Temperature and Reused Treated Wastewater [avtemp and wwtr]: No significant correlation was found [r = 0.03, p = 0.85]. Fluctuations in wastewater reuse volumes did not align with changes in temperature, indicating that temperature is not a major driver of wastewater reuse. External influences such as regulatory policies, economic factors, and technological advancements in wastewater treatment may play a more substantial role in determining reuse rates.

Average Rainfall and Reused Treated Wastewater [avrain and wwtr]: No clear inverse correlation was observed [r = −0.07, p = 0.66]. While it could be expected that higher rainfall would reduce the need for reused wastewater, the data do not support this, suggesting that other factors influence wastewater reuse. For instance, infrastructure investments may impact how reused wastewater is utilized, irrespective of rainfall levels.

Total Treated Wastewater and Reused Treated Wastewater [wwt and wwtr]: A positive correlation was identified [r = 0.75, $p < 0.01$], indicating that increased treatment capacity results in greater volumes of wastewater reuse. This reflects improved infrastructure and operational efficiency. However, financial investments, governmental policies promoting water recycling, and advancements in treatment technologies are also critical in enhancing wastewater treatment capacities and subsequent reuse.

5.2. Air Emissions and Environmental Factors

Air Emissions and Average Temperature [airem and avtemp]: A strong negative correlation was observed [r = −0.65, $p < 0.01$], suggesting that higher air emissions are linked to lower temperatures. This may reflect regional or temporal variations in emissions and temperature patterns influenced by industrial activity, urbanization, and energy consumption, which can skew temperature measurements in heavily polluted areas.

Air Emissions and Rainfall [airem and avrain]: A weak positive correlation [r = 0.20, p = 0.25] suggests that air emissions have a marginal impact on rainfall. This relationship may be affected by broader climatic factors, such as atmospheric circulation patterns and pollution levels, which can influence local weather phenomena.

Air Emissions and Transpiration Index [airem and indtran]: Similarly, a weak positive correlation was noted [r = 0.15, p = 0.40], indicating minimal influence of air emissions on transpiration rates. The lack of a strong connection may result from other environmental stressors, such as soil conditions and plant health, which can overshadow the impact of air quality on transpiration.

Air Emissions and Reused Treated Wastewater [airem and wwtr]: A strong negative correlation [r = −0.70, $p < 0.01$] indicates that higher air emissions are associated with lower volumes of reused wastewater, possibly due to environmental or operational constraints affecting wastewater treatment processes. External factors such as regulatory standards for air quality and wastewater treatment may limit the capacity for reuse in more polluted regions.

Air Emissions and Total Treated Wastewater [airem and wwt]: A strong negative correlation was also found [r = −0.68, $p < 0.01$], suggesting that higher emissions are associated with reduced wastewater treatment volumes. This may reflect infrastructural challenges or decreased treatment capacity influenced by local economic conditions, operational costs, and investment in treatment technologies.

5.3. Operational Performance of Wastewater Treatment (2015–2021)

The operational performance of wastewater treatment [WWT] companies from 2015 to 2021, as shown in Table 3, reveals several key trends:

Table 3. Data on WWT companies' operational performance, 2015–2021.

Year	owwt	ee	plan	ppe	rebcol	overuse	subuse
2015				21,184,175			
2016	4,594,636			28,935,192	5.9	211,217,428	572,569,531
2017				38,530,736		87,043,828	
2018	4,636,233			28,632,236	1.5		565,972,931
2019	4,121,440			30,082,235		77,983,258	366,244,545
2020	4,831,786	0.45	77	28,252,982	4.9	81,679,347	404,050,793
2021	4,269,111	0.58	66	39,782,954	0.30	86,512,167	608,942,223

Treated Wastewater Reused for Internal Purposes [owwt]: Increased gradually from 2016, peaking at 4.83 million m^3 in 2020, before slightly declining in 2021. This indicates a growing commitment to internal water reuse, possibly driven by operational efficiency and sustainability goals.

Energy Efficiency [ee]: The energy efficiency of pumping stations was first recorded in 2020, starting at 0.45 kWh/m^3 and increasing to 0.58 kWh/m^3 in 2021. This modest improvement reflects progress in energy efficiency, likely linked to energy efficiency plans [plan] implemented by wastewater companies.

Own Energy Production [ppe]: Demonstrated a consistent upward trend, from 21.18 million kWh in 2015 to 39.78 million kWh in 2021. This increase reflects growing adoption of renewable energy technologies, such as biogas, within wastewater treatment plants, supporting environmental and sustainability objectives.

Rehabilitation of Wastewater Collectors [rebcol]: Fluctuated significantly, with over 5.9 million m^3 of collectors rehabilitated in 2016, followed by a sharp drop in 2018 to 1.5 million m^3. Rehabilitation efforts peaked again in 2021 at 0.30 million m^3. These variations may reflect differences in infrastructure deterioration and funding availability for repair projects.

Overuse and Subuse of Treatment Plants: Overuse ranged from 77 million m^3 in 2019 to 87 million m^3 in 2017, indicating relatively consistent pressure on wastewater plant capacity. In contrast, subuse exhibited more variation, with notable underutilization in 2016 [572 million m^3] and 2018 [565 million m^3], which decreased by 2020 and 2021 [404 and 608 million m^3, respectively].

These patterns indicate operational challenges in balancing capacity across plants, with some being overburdened while others remain underutilized.

6. Discussion

This study confirms the central hypothesis that integrating advanced system designs, future climate projections, and regulatory frameworks can enhance the sustainability and effectiveness of water management practices in Portugal. The results support the idea that advanced water management systems, such as rainwater harvesting and improved wastewater treatment facilities, contribute to increased system efficiency. This is consistent with previous studies, such as those by Santos et al. [15], who also found that advanced system designs positively influence reclaimed water usage and sustainability. The positive correlation between advanced infrastructure and reclaimed water usage highlights that these systems play a significant role in improving cost-effectiveness and sustainability in Portugal.

Regarding future climate projections, the study reveals that climate change, particularly changes in rainfall patterns, can positively influence the performance of rainwater harvesting systems, especially in regions like Oporto and Vila Real. This is in line with findings from Santos et al. [15], who reported improvements in rainwater harvesting yields due to climate change. However, this study does not find a clear correlation between average rainfall levels and wastewater reuse, which contrasts with the literature, suggesting that higher rainfall may reduce the need for wastewater reuse. The inertia in the variation of values may be attributed to the significant amount of water reused within the wastewater treatment plants (WWTPs) themselves. This internal consumption is utilized in various stages of the treatment process, including primary treatment and filtration, and is less influenced by recorded rainfall. Thus, the noted discrepancy may be due to the complex interplay of factors influencing wastewater reuse, such as infrastructure efficiency and regulatory frameworks, which may play a more significant role in determining reuse rates.

The role of regulatory frameworks is another key finding of the study, aligning with the literature. This study's results, including the positive correlation between wastewater treatment infrastructure and treated wastewater reuse, emphasize the importance of regulations and incentives in enhancing the efficiency and resilience of water management practices. This supports the conclusions of previous studies, such as those by Matos et al. [38], which indicated that better wastewater treatment facilities result in higher reuse rates. The need for robust regulatory frameworks is further corroborated by the study's finding that stricter environmental standards and financial incentives for reclaimed water use could promote more sustainable practices.

This study also reveals that while climate factors like temperature and rainfall do influence water management in Portugal, operational factors, infrastructure efficiency, and regulatory frameworks may play a more decisive role. For example, the assumption that higher temperatures would lead to increased transpiration and higher water usage, thus increasing wastewater reuse, was not supported by the study's data. This contrasts with earlier literature that suggested a direct link between temperature, water usage, and wastewater reuse, highlighting the importance of non-climatic factors in influencing water management outcomes.

Additionally, the positive correlation between total treated wastewater and reused treated wastewater supports previous findings, such as those from Matos et al. [38], which highlighted that improved wastewater treatment infrastructure is directly linked to higher rates of wastewater reuse. This underscores the importance of continuing to invest in and modernize wastewater treatment facilities as a critical component of sustainable water management.

In terms of environmental impacts, the study's finding of a strong negative correlation between air emissions and wastewater reuse adds nuance to the literature on the relationship between environmental factors and water management. While earlier studies suggested that temperature and emissions could influence water reuse, this study indicates that operational constraints—such as emissions and the energy intensity of wastewater treatment processes—may play a more significant role in determining wastewater reuse rates.

Operational data from wastewater treatment companies show improvements in efficiency between 2015 and 2021, but inefficiencies still persist, highlighting the need for further enhancements in operational practices to fully realize the potential of wastewater treatment and reuse. The underutilization of treatment plants in 2016 and 2018 underscores the gap between available infrastructure and operational efficiency, emphasizing the importance of better aligning policy frameworks with infrastructure investments. Stable investments are crucial for maintaining competitiveness and sustainability in resource management sectors [57].

This study also reveals a positive correlation between energy efficiency, internal energy production, and increased volumes of reused wastewater, indicating progress in the sustainability of wastewater treatment operations. The rise in biogas use and renewable energy integration contributes to broader environmental sustainability goals. Notably, the increased energy efficiency of pumping stations observed in 2020 demonstrates how wastewater treatment plants are successfully incorporating renewable energy sources.

However, the negative correlation between air emissions and wastewater reuse suggests that pollution remains a challenge, particularly in industrial areas. This requires innovation and adaptation, not only in the business sector but also in wastewater treatment operations. In this context, wastewater treatment plants, especially in areas with high pollution, must have the flexibility to innovate, integrate new technologies, and reduce emissions to ensure long-term sustainability and resilience [58].

Based on these results, several key policy actions are recommended. First, continued investment in advanced water management infrastructure is crucial, including the expansion of wastewater treatment facilities and the promotion of rainwater harvesting systems, particularly in areas with increased rainfall variability. Incorporating climate change projections into water management planning is essential to ensure resilience against changing climatic conditions, especially in regions like Oporto and Vila Real, where rainfall variability has a direct impact on system performance.

This study also emphasizes the need for enhanced regulatory frameworks, particularly for wastewater treatment and reuse. Policies should incentivize the expansion of wastewater treatment capacities and set stricter environmental standards for water management practices. Public awareness and education campaigns should promote the benefits of reclaimed water, fostering acceptance and overcoming public resistance to water reuse technologies. This would align with the earlier work by Santos et al. [15], which highlighted the importance of regulatory incentives and public engagement in promoting water reuse.

Finally, addressing operational inefficiencies in wastewater treatment companies is essential. Optimizing resource use, supporting innovation, and better monitoring of operational performance can help reduce costs and environmental impacts while improving efficiency. Government support for research into new technologies and alternative energy sources for wastewater treatment can further enhance sustainability. These recommendations underscore the importance of a multi-faceted approach, combining infrastructure improvements, regulatory reforms, and operational efficiency, to achieve sustainable water management in Portugal.

In conclusion, the findings suggest that while climate change and advanced infrastructure are critical, operational factors and regulatory frameworks are equally important in driving improvements in water management and wastewater reuse.

7. Conclusions

This study provides critical insights into the relationship between climate trends and wastewater management in Portugal, showcasing both progress and ongoing challenges. The results indicate a clear increase in the use of reclaimed wastewater and notable improvements in energy efficiency within wastewater treatment facilities, aligning with broader sustainability goals. This upward trend in wastewater reuse, despite climatic variability, highlights the effectiveness of adaptation strategies in managing water scarcity. However, gaps in infrastructure investment and the need for region-specific adaptation measures reveal inefficiencies that hinder the optimal performance of these strategies. By integrating climate data with wastewater management performance metrics, this research offers a nuanced view of how climate variability impacts water reuse and treatment processes. The study underscores the *effectiveness* of adaptation strategies in increasing water reuse and energy efficiency but also points to *efficiency* challenges, particularly in infrastructure underutilization and inconsistent investment. These distinctions provide a more detailed understanding of how climate change affects wastewater management and reinforce the need for dynamic, region-specific policies. Additionally, the study's findings on energy efficiency and the incorporation of renewable energy sources contribute to the broader knowledge base on sustainable water management. Despite its contributions, this study is subject to several limitations. The data analyzed only span from 2015 to 2021, which may not capture longer-term trends or the effects of recent climate events. Additionally, the reliance on aggregate data may obscure regional differences and specific local challenges in wastewater management. The analysis focuses primarily on air emissions and temperature, without accounting for other environmental variables that could influence wastewater management performance.

Future research should address these limitations by expanding the dataset to cover more recent periods and delve deeper into regional variations. Longitudinal studies could provide a clearer view of long-term trends and the success of newer adaptation measures. Furthermore, integrating a wider range of environmental factors and exploring their interactions with wastewater management would offer a more holistic understanding. Future research should also assess the role of emerging technologies and socio-economic factors in shaping wastewater management practices. Investigating public perceptions and educational initiatives could help overcome social barriers to the use of reclaimed water, fostering wider acceptance and implementation of sustainable water practices.

Funding: This research is financed by National Funds of the FCT—Portuguese Foundation for Science and Technology within the project «UIDB/04928/2020» and under the Scientific Employment Stimulus-Institutional Call CEECINST/00051/2018.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Fernandes, L.F.S.; Terêncio, D.P.; Pacheco, F.A. Rainwater harvesting systems for low demanding applications. *Sci. Total Environ.* **2015**, *529*, 91–100. [CrossRef] [PubMed]
2. Asif, Z.; Chen, Z.; Sadiq, R.; Zhu, Y. Climate change impacts on water resources and sustainable water management strategies in North America. *Water Resour. Manag.* **2023**, *37*, 2771–2786. [CrossRef]
3. Taye, M.T.; Haile, A.T.; Fekadu, A.G.; Nakawuka, P. Effect of irrigation water withdrawal on the hydrology of the Lake Tana sub-basin. *J. Hydrol. Reg. Stud.* **2021**, *38*, 100961. [CrossRef]
4. Blair, P.; Buytaert, W. Socio-hydrological modelling: A review asking "why, what and how?". *Hydrol. Earth Syst. Sci.* **2006**, *20*, 443–478. [CrossRef]
5. Luo, M.; Liu, T.; Meng, F.; Duan, Y.; Bao, A.; Xing, W.; Feng, X.; Maeyer, P.D.; Frankl, A. Identifying climate change impacts on water resources in Xinjiang, China. *Sci. Total Environ.* **2019**, *676*, 613–626. [CrossRef] [PubMed]
6. Kundzewicz, Z.W.; Krysanova, V.; Benestad, R.E.; Hov, Ø.; Piniewski, M.; Otto, I.M. Uncertainty in climate change impacts on water resources. *Environ. Sci. Policy* **2018**, *79*, 1–8. [CrossRef]
7. Wilby, R.L.; Whitehead, P.G.; Wade, A.J.; Butterfield, D.; Davis, R.J.; Watts, G. Integrated modelling of climate change impacts on water resources and quality in a lowland catchment: River Kennet, UK. *J. Hydrol.* **2006**, *330*, 204–220. [CrossRef]
8. Sivakumar, B. Global climate change and its impacts on water resources planning and management: Assessment and challenges. *Stoch. Environ. Res. Risk Assess.* **2011**, *25*, 583–600. [CrossRef]
9. Hamid, A.T.; Sharif, M.; Narsimlu, B. Assessment of climate change impacts on streamflows in Satluj river basin, India using SWAT model. *Int. J. Hydrol. Sci. Technol.* **2017**, *7*, 134–157. [CrossRef]
10. Schilling, J.; Hertig, E.; Tramblay, Y.; Scheffran, J. Climate change vulnerability, water resources and social implications in North Africa. *Reg. Environ. Chang.* **2020**, *20*, 1–12. [CrossRef]

11. Rosli, M.H. *Development of an Integrated Spatial Distributed Travel Time Method Using GIS to Model Rainfall Runoff in Bentong Catchment in Peninsular Malaysia*; Universiti Putra Malaysia (UPM): Serdang, Malaysia, 2018.
12. Griffin, R.C. *Water Resource Economics: The Analysis of Scarcity, Policies, and Projects*; MIT Press: Cambridge, MA, USA, 2016.
13. Pordata. 2023. Available online: www.pordata.pt (accessed on 15 September 2024).
14. Lúcio, C.; Silva, C.M.; Sousa, V. A scale-adaptive method for urban rainwater harvesting simulation. *Environ. Sci. Pollut. Res.* **2020**, *27*, 4557–4570. [CrossRef] [PubMed]
15. Santos, C.; Imteaz, M.A.; Ghisi, E.; Matos, C. The effect of climate change on domestic Rainwater Harvesting. *Sci. Total Environ.* **2020**, *729*, 138967. [CrossRef] [PubMed]
16. Varma, V.C.; Rathinam, R.; Suresh, V.; Naveen, S.; Satishkumar, P.; Abdulrahman, I.S.; Salman, H.M.; Singh, P.; Kumar, J.A. Urban waste water management paradigm evolution: Decentralization, resource recovery, and water reclamation and reuse. *Environ. Qual. Manag.* **2024**, *33*, 523–540. [CrossRef]
17. Miller, G.W. Integrated concepts in water reuse: Managing global water needs. *Desalination* **2006**, *187*, 65–75. [CrossRef]
18. Laitinen, J. Quest for Sustainable Urban Water Services: Management and Practices in Finland. Doctoral Dissertation, Faculty of Built Environment, Tampere University, Tampere, Finland, 2020. Available online: https://trepo.tuni.fi/handle/10024/122793 (accessed on 15 September 2024).
19. Moreira da Silva, M.; Resende, F.C.; Freitas, B.; Aníbal, J.; Martins, A.; Duarte, A. Urban Wastewater Reuse for Citrus Irrigation in Algarve, Portugal—Environmental Benefits and Carbon Fluxes. *Sustainability* **2022**, *14*, 10715. [CrossRef]
20. Afonso, M.J.; Freitas, L.; Chaminé, H.I. Groundwater recharge in urban areas [Porto, NW Portugal]: The role of GIS hydrogeology mapping. *Sustain. Water Resour. Manag.* **2019**, *5*, 203–216. [CrossRef]
21. Santos, E.; Lisboa, I.; Eugénio, T. Economic sustainability in wastewater treatment companies: A regional analysis for the Iberian Peninsula. *Appl. Sci.* **2021**, *11*, 9876. [CrossRef]
22. Malmsheimer, R.W.; Heffernan, P.; Brink, S.; Crandall, D.; Deneke, F.; Galik, C.; Gee, E.; Helms, J.A.; McClure, N.; Mortimer, M.; et al. Forest management solutions for mitigating climate change in the United States. *J. For.* **2008**, *106*, 115–173. [CrossRef]
23. Da Cunha, L.V.; De Oliveira, R.P.; Nascimento, J.; Ribeiro, L. Impacts of climate change on water resources: A case-study for Portugal. *IAHS Publ.* **2007**, *310*, 37.
24. Dannenberg, A.; Mennel, T.; Osberghaus, D.; Sturm, B. *The Economics of Adaptation to Climate Change-the Case of Germany*; ZEW-Centre for European Economic Research Discussion Paper, (09-057); Leibniz Centre for European Economic Research: Mannheim, Germany, 2009.
25. Arroyo, V.; Zyla, K.A.; Pacyniak, G.; Deas, M. State Innovation on Climate Change: Reducing Emmissions from Key Sectors While Preparing for a New Normal. *Harv. L. Pol'y Rev.* **2016**, *10*, 385.
26. Mendes, M.P. Exploring the Development of an Energy Efficiency One-Stop Shop. Master's Thesis, Universidade NOVA de Lisboa, Lisbon, Portugal, 2022.
27. Santo, F.E.; Guerreiro, R.I.T.A.; Pires, V.C.; Pessanha, L.E.; Gomes, I.M. Monitoring agricultural drought in mainland Portugal. In *Monitoring and Predicting Agricultural Drought: A Global Study*; Boken, V.K., Cracknell, A.P., Heathcote, R.L., Eds.; Oxford University Press: New York, NY, USA, 2005; pp. 181–195.
28. Do, Ó. Drought risk management in the Mediterranean under the Water Framework Directive—The example of Algarve. *WIT Trans. Ecol. Environ.* **2007**, *103*, 81–90. (In Portugal)
29. Lopes, C.M.; Costa, J.M.; Egipto, R.; Zarrouk, O.; Chaves, M.M. Can Mediterranean terroirs withstand climate change? Case studies at the Alentejo Portuguese winegrowing region. *E3S Web Conf.* **2018**, *50*, 01004. [CrossRef]
30. Maia, R.; Vicente-Serrano, S.M. Drought Planning and Management in the Iberian Peninsula. In *Drought and Water Crises*; CRC Press: Boca Raton, FL, USA, 2017; pp. 481–506.
31. Romero, P.; Navarro, J.M.; Ordaz, P.B. Towards a sustainable viticulture: The combination of deficit irrigation strategies and agroecological practices in Mediterranean vineyards. A review and update. *Agric. Water Manag.* **2022**, *259*, 107216. [CrossRef]
32. Santos, F.L.; Valverde, P.C.; Ramos, A.F.; Reis, J.L.; Castanheira, N.L. Water use and response of a dry-farmed olive orchard recently converted to irrigation. *Biosyst. Eng.* **2007**, *98*, 102–114. [CrossRef]
33. Pulido-Calvo, I.; Gutiérrez-Estrada, J.C.; Sanz-Fernández, V. Drought and ecological flows in the lower Guadiana river basin [Southwest Iberian Peninsula]. *Water* **2020**, *12*, 677. [CrossRef]
34. Conceição, N.; Tezza, L.; Häusler, M.; Lourenço, S.; Pacheco, C.A.; Ferreira, M.I. Three years of monitoring evapotranspiration components and crop and stress coefficients in a deficit irrigated intensive olive orchard. *Agric. Water Manag.* **2017**, *191*, 138–152. [CrossRef]
35. Levidow, L.; Zaccaria, D.; Maia, R.; Vivas, E.; Todorovic, M.; Scardigno, A. Improving water-efficient irrigation: Prospects and difficulties of innovative practices. *Agric. Water Manag.* **2014**, *146*, 84–94. [CrossRef]
36. Rocha, J.; Carvalho-Santos, C.; Diogo, P.; Beça, P.; Keizer, J.J.; Nunes, J.P. Impacts of climate change on reservoir water availability, quality and irrigation needs in a water scarce Mediterranean region (southern Portugal). *Sci. Total Environ.* **2020**, *736*, 139477. [CrossRef]
37. Zarrouk, O.; Costa, J.M.; Francisco, R.; Lopes, C.; Chaves, M.M. Drought and water management in Mediterranean vineyards. In *Grapevine in a Changing Environment*; John Wiley & Sons, Inc.: Hoboken, NJ, USA, 2015; pp. 38–67.
38. Matos, C.; Bentes, I.; Santos, C.; Imteaz, M.; Pereira, S. Economic analysis of a rainwater harvesting system in a commercial building. *Water Resour. Manag.* **2015**, *29*, 3971–3986. [CrossRef]

39. Kiełkowska, J.; Tokarczyk-Dorociak, K.; Kazak, J.; Szewrański, S.; Van Hoof, J. Urban adaptation to climate change plans and policies–the conceptual framework of a methodological approach. *J. Ecol. Eng.* **2018**, *19*, 50–62. [CrossRef] [PubMed]
40. Monteiro, R.; Ferreira, J.C. Green infrastructure planning as a climate change and risk adaptation tool in coastal urban areas. *J. Coast. Res.* **2020**, *95*, 889–893. [CrossRef]
41. Staddon, C.; Ward, S.; De Vito, L.; Zuniga-Teran, A.; Gerlak, A.K.; Schoeman, Y.; Hart, A.; Booth, G. Contributions of green infrastructure to enhancing urban resilience. *Environ. Syst. Decis.* **2018**, *38*, 330–338. [CrossRef]
42. Khodadad, M.; Aguilar-Barajas, I.; Khan, A.Z. Green infrastructure for urban flood resilience: A review of recent literature on bibliometrics, methodologies, and typologies. *Water* **2023**, *15*, 523. [CrossRef]
43. Li, L. Green Infrastructures to Mitigate the Urban Surface Water Flooding Risk: Identifying and Planning the Priority Areas in Ghent. Doctoral Dissertation, Ghent University, Ghent, Belgium, 2020.
44. Monteiro, R.; Ferreira, J.C.; Antunes, P. Green infrastructure planning principles: Identification of priorities using analytic hierarchy process. *Sustainability* **2022**, *14*, 5170. [CrossRef]
45. Silva, C.M.; Flores-Colen, I.; Antunes, M. Step-by-step approach to ranking green roof retrofit potential in urban areas: A case study of Lisbon, Portugal. *Urban For. Urban Green.* **2017**, *25*, 120–129. [CrossRef]
46. Grădinaru, S.R.; Hersperger, A.M. Green infrastructure in strategic spatial plans: Evidence from European urban regions. *Urban For. Urban Green.* **2019**, *40*, 17–28. [CrossRef]
47. Ferreira, A.; Sousa, V.; Pinheiro, M.; Meireles, I.; Silva, C.M.; Brito, J.; Mateus, R. Potential of rainwater harvesting in the retail sector: A case study in Portugal. *Environ. Sci. Pollut. Res.* **2023**, *30*, 42427–42442. [CrossRef] [PubMed]
48. *NP 4434:2005*; Água Reutilizada para Usos Não Potáveis. Instituto Português da Qualidade: Lisboa, Portugal, 2005.
49. Sanz, L.A.; Gawlik, B.M. *Water Reuse in Europe. Relevant Guidelines, Needs for and Barriers to Innovation. A Synoptic Overview*; European Commission, Joint Research Centre and Institute for Environment and Sustainability: Ispra, Italy, 2014.
50. Portugal. Decree-Law No. 119/2019 of August 21, 2019. Diário da República, 1.ª Série, No. 162, pp. 4876–4896. 2019. Available online: https://www.dre.pt/pesquisa/-/search/116657352/details/maximized (accessed on 15 September 2024).
51. *ISO 20760-1:2017*; Water Reuse in Urban Areas—Guidelines for Centralized Water Reuse System—Part 1: Design Principles of a Centralized Water Reuse System. International Organization for Standardization: Geneva, Switzerland, 2017. Available online: https://www.iso.org/standard/65185.html (accessed on 15 September 2024).
52. European Union. Regulation (EU) 2020/741 of the European Parliament and of the Council of 25 May 2020 on Minimum Requirements for Water Reuse. Official Journal of the European Union. 2020. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32020R0741 (accessed on 15 September 2024).
53. Rebelo, A.; Quadrado, M.; Franco, A.; Lacasta, N.; Machado, P. Water reuse in Portugal: New legislation trends to support the definition of water quality standards based on risk characterization. *Water Cycle* **2020**, *1*, 41–53. [CrossRef]
54. Bixio, D.; Thoeye, C.; De Koning, J.; Joksimovic, D.; Savic, D.; Wintgens, T.; Melin, T. Wastewater reuse in Europe. *Desalination* **2006**, *187*, 89–101. [CrossRef]
55. Mesa-Pérez, E.; Berbel, J. Analysis of barriers and opportunities for reclaimed wastewater use for agriculture in Europe. *Water* **2020**, *12*, 2308. [CrossRef]
56. Santos, A.F.; Alvarenga, P.; Gando-Ferreira, L.M.; Quina, M.J. Urban wastewater as a source of reclaimed water for irrigation: Barriers and future possibilities. *Environments* **2023**, *10*, 17. [CrossRef]
57. Santos, E.; Castanho, R.A.; Meyer, D. Is investment contributing to competitiveness in nautical tourism in the atlantic area? *Water* **2022**, *14*, 2964. [CrossRef]
58. Santos, E.; Castanho, R.A. The impact of size on the performance of transnational corporations operating in the textile industry in Portugal during the COVID-19 pandemic. *Sustainability* **2022**, *14*, 717. [CrossRef]