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An Integrated Approach for the Sustainable Water Resources Optimization

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ABSTRACT

Ensuring access to clean water, preserving water reserves, and meeting energy needs are fundamental for sustainability and a priority for global organizations like the UN and EU. The Mediterranean, particularly Greece, faces severe water imbalances due to rising demand, prolonged droughts, and seasonal tourism pressure. This over-exploitation of water resources threatens agriculture, employment, and regional sustainability. Addressing these challenges, this study analyzes the water-energy nexus in high-stress areas and develops an optimization model for sustainable water resource management. The model integrates sectoral demands, energy consumption, and seasonal variability to improve efficiency while balancing economic and environmental constraints. Additionally, it incorporates demand forecasting to align water use with ecosystem sustainability, reducing environmental impacts. By providing a systematic framework for decision-makers, this research supports the development of long-term, resilient water management strategies, ensuring efficient resource allocation in vulnerable regions. The findings will contribute to sustainable water policies and infrastructure planning.

Keywords: water resources, water-energy nexus, water sustainability, optimisation, mathematical model

1. INTRODUCTION

Water is vital for human survival, socio-economic development, and ecological balance. However, global water scarcity is intensifying due to rising demand and the impacts of climate change. Approximately 844 million people currently lack access to safe drinking water, and nearly 2 billion live in areas of high water stress. By 2050, water demand is expected to rise by 30%, further straining resources and exacerbating challenges in already water-stressed regions [1].

The Mediterranean region, home to over 500 million people, is particularly vulnerable to these challenges. Renewable water resources are estimated at 1,500 km^3 annually, but their distribution is highly uneven: 74% is available in the north, 21% in the east, and only 5% in the south. Agriculture, which accounts for over 65% of the region's water withdrawals, is especially at risk from shortages, jeopardizing food security and economic stability [2]. In Greece, seasonal and geographic dynamics compound the issue. The influx of tourists during the summer months significantly increases water stress, particularly in island regions where reserves are already limited. Overexploitation of aquifers has led to the depletion of water reserves, with negative impacts on agriculture, biodiversity, and local economies. Reduced irrigation capacity has contributed to declining agricultural productivity and a shrinking workforce in the sector. These issues are further exacerbated by climate change, which causes prolonged droughts, increased temperatures, and the salinization of freshwater sources, severely diminishing the availability of potable water [2].

Another critical factor is the water-energy nexus, reflecting the interdependence between water and energy systems. Globally, water systems—including supply, treatment, distribution, and wastewater management—consume approximately 7% of total electricity. Drinking water treatment requires energy inputs ranging from 0.4–3 kWh/m^3, while seawater desalination, increasingly relied upon in arid regions, demands 3.9–4.3 kWh/m^3, making it one of the most energy-intensive processes. This interconnection highlights the need for integrated strategies that address both water and energy demands efficiently [3].

Sustainable water management is essential for addressing these challenges. Optimization techniques like linear programming, mixed-integer programming, and dynamic simulations enhance resource allocation, reduce losses, and lower energy consumption. Studies show these models can cut leakage rates by up to 30% and achieve 15–20% energy savings in urban water systems [4]. Recognizing the urgency, the EU has prioritized water optimization in its 2030 agenda, promoting smart management technologies like real-time monitoring to reduce inefficiencies and expand clean water access to 70 million citizens [5]. These measures align with sustainability goals and mitigate climate change impacts.

This study explores advanced optimization techniques to balance water resource allocation and energy consumption while adhering to sustainability goals. By integrating innovative tools and approaches, it aims to deliver actionable solutions for sustainable water management, ensuring resilience and alignment with broader climate and development objectives.

2. CURRENT SITUATION

2.1. Global and economic impact of water scarcity

Despite notable advancements in water management technologies and infrastructure, water scarcity continues to be a pressing global challenge and is recognized as one of the most critical risks for the coming decade. Globally, over 2 billion people are living in regions of high water stress, with projections indicating that this number will increase due to population growth, urbanization, and climate change. Additionally, 1 billion people lack access to clean and safe drinking water, leading to significant health crises, including 3.4 million deaths annually caused by water-related diseases [6].

Agriculture consumes over 80% of global freshwater resources, making it the most vulnerable sector to water shortages, especially in arid and semi-arid regions where irrigation is critical for food production [7]. Urbanization and industrial activities further exacerbate the strain on water availability, highlighting the urgent need for sustainable water resource management. The financial repercussions of droughts, which often exacerbate water scarcity, are substantial. In the United States, annual drought damages are estimated between $2 billion and $6 billion, while in the European Union, these losses amount to approximately $3 billion annually [8]. These costs represent 0.05% to 0.1% of the GDP, though in particularly severe years, the economic burden can rise dramatically, impacting multiple sectors, including agriculture, industry, and domestic water use [9].

2.2. Water scarcity in Mediterranean and Greece

The Mediterranean region is home to over 500 million people, with population growth and trends varying across the 24 countries in the area. Between 2008 and 2018, the population increased by **11%**, adding further strain to the region's already limited water resources [1]. The annual water requirement in the Mediterranean, estimated to range between 500 and 1000 m³ per capita, has risen due to the combined pressures of population growth, urbanization, and the expansion of irrigated agriculture [10]. Currently, the region is classified as "water-poor," with less than 1000 m³ of water available per person annually. According to United Nations projections, this water scarcity will intensify, potentially affecting 250 million people by 2040 [1].

Greece possesses a sufficient overall supply of water resources; however, significant challenges remain in ensuring their efficient utilization and management. This is particularly true given the country's distinct geographical features and climatic variability. Greece generates approximately 72 km³ of renewable freshwater annually, while its annual water consumption stands at about 9.5 km³. Water consumption is also heavily influenced by land use patterns, with agriculture being the dominant user. Depending on the district, agricultural water usage ranges from 11% to 92%, with a national average of approximately 74% [11].

3. WATER-ENERGY NEXUS

3.1. The dynamic interdependence of the water-energy nexus

Water and energy are intricately interconnected, forming a complex relationship that varies at local and regional levels. Communities rely on water for a wide range of purposes, including residential, commercial, industrial, recreational, and agricultural activities. In urban water systems specifically, energy plays a critical role in every stage of the water management cycle, from intake and purification to transmission, distribution, sewage collection, treatment, recycling, and discharge back into natural waterways. This interdependence becomes even more evident as an increase in water demand directly drives a required to manage these resources efficiently [12].

For instance, one study [13] highlighted that groundwater abstraction for drinking water requires significantly higher energy consumption compared to surface water abstraction, demonstrating the energy demands of different water sources. Similarly, research [14] in Germany found that reducing fossil fuel production contributed to alleviating water stress, emphasizing the interconnection between energy policies and water resources. The importance of minimizing energy use in water and wastewater treatment systems has also been underscored [15], as this can yield substantial environmental and economic benefits. Furthermore, factors such as water use patterns, topography, climate, and operational efficiencies significantly influence energy intensities in water purification processes, highlighting the need for tailored strategies to optimize energy use in specific contexts[16].

3.2. Navigating challenges and innovations in the water-energy nexus

The intricate balance between water and energy resources presents significant challenges that are often compounded by trade-offs inherent in their interdependence. For instance, desalination, a vital water source in arid regions, is highly energy-intensive, raising concerns about its environmental and economic sustainability, especially in energy-scarce areas. Similarly, thermoelectric power generation, which relies heavily on water for cooling, is vulnerable to water shortages, particularly in regions experiencing droughts or increased competition for water resources. These examples illustrate how actions to secure one resource can inadvertently strain the other, emphasizing the need for integrated and sustainable approaches to resource management [17].

To address these challenges, technological innovations offer promising solutions. Advances in energy-efficient desalination technologies, such as reverse osmosis membranes with enhanced permeability and durability, are helping to reduce the energy footprint of water production. Similarly, adopting renewable energy sources, such as solar and wind power, for water management processes like pumping, desalination, and wastewater treatment significantly mitigates the reliance on fossil fuels, thereby reducing greenhouse gas emissions. Additionally, smart water systems that incorporate IoT and big data analytics enable real-time monitoring and optimization of water distribution networks, minimizing energy losses and improving overall efficiency [18, 19].

4. OPTIMISATION

4.1. Optimising water supply systems within the water-energy nexus

Efficient design, management, and planning of water supply systems with a focus on the water-energy nexus can preserve resources and reduce avoidable costs in investments, operations, and management. However, optimization challenges in this nexus have primarily been addressed from either a water or energy perspective, with limited studies focusing on their simultaneous optimization [20, 21].

To bridge these gaps, recent research emphasizes integrative frameworks for dual optimization of water and energy. Multi-objective models have been developed to minimize costs, improve resource efficiency, and mitigate environmental impacts, enabling decision-makers to optimize both systems concurrently and achieve a more sustainable and resilient nexus [22, 23].

One notable strategy is the application of mixed-integer linear programming (MILP) and graphical methods to identify optimal solutions. MILP-based models provide precision and adaptability, accommodating complex interdependencies between water supply systems and energy demands. Similarly, graphical optimization techniques, such as composite curves, visually represent resource flows and help pinpoint the minimum water and energy requirements for a given demand, as demonstrated in case studies like Spain's water-energy nexus [23].

4.2. Integrated approaches, challenges and future directions

Integrated approaches are particularly effective in urban areas, where centralized and decentralized systems coexist. Platforms like resilience.io employ agent-based modeling to simulate the spatiotemporal dynamics of resource demand and supply [22]. These simulations facilitate informed planning by considering factors such as demographic changes, urbanization, and renewable energy integration. Moreover, technological innovations play a vital role in optimizing the water-energy nexus. Renewable energy-powered water treatment facilities and decentralized systems have emerged as promising solutions to address resource constraints. For instance, integrating solar-powered desalination systems can significantly reduce energy consumption in water-scarce regions [23]. Despite progress, several challenges remain in advancing nexus optimization. Key issues include the lack of comprehensive datasets, computational limitations in large-scale models, and the need to account for uncertainties such as climate variability and fluctuating resource demands. Future research should prioritize several key areas to advance understanding and practical solutions within the water-energy nexus. First, there is a pressing need to develop adaptive and scalable models that incorporate stochastic variables and scenario-based analyses, allowing for more accurate predictions and better handling of uncertainties. Second, improving data availability and quality is crucial to enhance the accuracy of models and support informed decision-making processes. High-resolution, reliable data can help identify trends, assess resource dependencies, and tailor solutions to specific contexts [24, 25].

5. MATHEMATICAL MODEL

5.1. Description

Water resource management in Greece faces significant challenges, especially in regions heavily influenced by tourism. Seasonal peaks during the summer tourist season create high water demand, intensifying the strain on limited water supplies. Furthermore, water extraction and distribution systems are energy-intensive, adding an additional layer of complexity due to environmental and economic considerations. As a result, a strategic approach is required to ensure the efficient and sustainable use of available resources.

To address these challenges, this study presents a linear optimization model designed to optimize water resource allocation while balancing costs, energy consumption, and environmental sustainability. The model integrates sectoral water demands, energy consumption, and seasonal variability to achieve a cost-effective and sustainable solution. Specifically, it is tailored for application in Greece, where water scarcity, tourism-driven seasonal demand, and high energy costs create significant management challenges. Regions such as the Greek islands (e.g., Crete, Cyclades) and mainland agricultural zones (e.g., Thessaly) serve as potential case studies for validating the model's effectiveness in optimizing water allocation and energy use.

The optimization model aims to minimize the total cost of water allocation, taking into account the direct costs of sourcing and distributing water, as well as the energy costs incurred during extraction and distribution. By applying this approach, the model provides a systematic framework for improving water management in high-demand regions, ensuring long-term sustainability while addressing socio-economic and environmental constraints.

The objective function is mathematically expressed as:

$$Z = \sum_{t=1} \sum_{i=1}^{n} \sum_{j=1}^{m} \left(C_{i,j}^{t} * x_{i,j}^{t} + E_i * P_i * x_{i,j}^{t} \right) \quad (1)$$

Where:

- Z: total cost to minimize
- t: index of the time periods (peak, off-season)
- i: index of water sources (i=1,...,n)
- j: index of water demand sectors (j=1,...,m)
- $C_{i,j}^{t}$: cost per unit of water ($/m³) from source i for sector j in season t
- $x_{i,j}^{t}$: volume of water allocated (m³) from source i to sector j in season t
- E_i: energy intensity of water source i (kWh/m³)
- Pi: energy cost for source i ($/kWh)

This function ensures that the water sourcing and energy costs are optimized over all sources, sectors, and seasons. In this model, t represents different time periods, specifically seasonal variations (e.g., peak and off-season demand). Thus, the total cost Z reflects the overall annual expenditure for water allocation and energy use, ensuring cost-effective and sustainable water distribution throughout the year.

5.2. Constraints

5.2.1. Water availability constraint

The total water extracted from each source i during season t cannot exceed its seasonal availabilityW_i^t, which is influenced by natural recharge rates, legal extraction limits, and infrastructure capacity. In Greece, the touristic season significantly amplifies water demand, especially in island regions and coastal areas. This seasonal surge often coincides with lower rainfall periods, intensifying stress on local water resources. The constraint ensures that extraction levels remain sustainable, balancing the needs of permanent residents and seasonal visitors without compromising long-term water availability. Planning for peak tourist seasons is critical to preventing overexploitation and ensuring sufficient reserves for off-peak periods.

$$\sum_{j=1}^{m} x_{i,j}^{t} \leq W_i^t, \ \forall\, i, t \quad (2)$$

5.2.2. Sectoral demand constraint

The total water allocated to each sector j during season t must at least meet its dynamic seasonal demandD_j^t. This demand is driven by factors such as peak tourist influx, crop-specific irrigation needs, and domestic water consumption. By ensuring sectoral demands are met, this constraint supports economic activities, such as agriculture and tourism, while safeguarding basic human needs. It also accounts for sector-specific priorities during water shortages; ensuring essential services like healthcare or food production are not compromised.

$$\sum_{i=1}^{n} x_{i,j}^{t} \geq D_j^t \ , \ \forall\, j, t \quad (3)$$

5.2.3. Energy sustainability constraint

The total energy required for water extraction and distribution must not exceed the allowable energy threshold E_{max}. This includes energy from renewable and non-renewable sources, factoring in energy efficiency and carbon reduction strategies. Energy sustainability is critical to managing the water-energy nexus, reducing operational costs, and achieving climate goals.

$$\sum_{t=1} \sum_{i=1}^{n} \sum_{j=1}^{m} \left(E_i * x_{i,j}^{t} \right) \leq E_{max} \quad (4)$$

5.2.4. Environmental sustainability constraint

The environmental impact of water sourcing, expressed as I_i, must remain within acceptable ecological limits I_{max}. The coefficient I_i represents the environmental impact per cubic meter of water extracted from source i. It can be measured in terms of greenhouse gas emissions (kg CO_2/m^3), water quality degradation (e.g., pollutant levels per m^3), or ecosystem disturbance (e.g., groundwater depletion rates). By enforcing this constraint, the model ensures that water sourcing remains within ecologically sustainable limits.. Adherence to this constraint helps minimize the degradation of natural habitats, ensure compliance with environmental regulations, and maintain biodiversity.

$$\sum_{t=1}\sum_{j=1}^{m} x_{i,j}^{t} * I_i \leq I_{max} \ , \ \forall i \quad (5)$$

5.2.5. Infrastructure capacity constraint

Each water source has an infrastructure capacity (F_i) limiting the maximum water that can be extracted during season t. This constraint considers the physical limits of pumps, pipelines, and storage facilities, as well as maintenance schedules and potential downtime. By enforcing these limits, the constraint prevents overloading of infrastructure and ensures its longevity. It also emphasizes the importance of planned infrastructure upgrades to accommodate future water demands without jeopardizing system reliability.

$$\sum_{j=1}^{m} x_{i,j}^{t} \leq F_i, \ \forall \, i,t \quad (6)$$

5.2.6. Non- negativity constraint

The non-negativity constraint ensures that all decision variables in the optimization model take non-negative values. In the context of water resource management, this constraint guarantees that the volume of water allocated from each source to each sector remains physically meaningful and prevents unrealistic negative values in calculations.

$$\sum_{j=1}^{m} x_{i,j}^{t} \leq F_i, \ \forall \, i,t \quad (7)$$

6. CONCLUSIONS AND FUTURE STEPS

6.1. Conclusions

This study presents an integrated optimization model for sustainable water resource management, addressing water scarcity challenges in regions like Greece and the Mediterranean. Seasonal demand fluctuations, climate change, and rising energy costs for water extraction and distribution intensify these issues. By analyzing the water-energy nexus, this research highlights the interdependencies between water availability, energy use, and economic sustainability, emphasizing the need for multi-objective resource management.

The model enhances water allocation efficiency while balancing economic, energy, and environmental factors. It considers sectoral demand variations, infrastructure constraints, and future consumption trends, ensuring resilient and adaptive distribution. Using multi-objective optimization, it maximizes resource efficiency, reduces losses, and promotes equitable distribution. Integrating renewable energy sources such as solar desalination and wind-assisted distribution can further enhance sustainability and reduce operational costs.

While this study primarily focuses on the model's formulation and theoretical framework, future research will focus on applying the model to real-world case studies. The next steps involve validating its effectiveness using data from Greek regions with high seasonal water demand, such as Aegean Islands. This practical application will allow for a detailed assessment of the model's performance in optimizing water allocation and minimizing environmental impact.

Future research should strengthen the water-energy nexus, embedding energy-efficient technologies like smart grids and wastewater recycling into water systems. Sectoral prioritization must be improved to ensure schools, hospitals, and homes receive priority during scarcity, supported by real-time data analytics. Advances in machine learning and AI-driven forecasting will improve demand predictions, while climate-resilient strategies and early warning systems will enhance preparedness. Expanding hybrid renewable energy solutions will further mitigate reliance on fossil fuels. By integrating these innovations, water-energy optimization can enhance resilience, sustainability, and socio-economic stability in water-stressed regions.

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