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CONTENTS

WATER SUPPLY CHALLENGES IN THE AEGEAN ISLANDS UNDER CLIMATE CHANGE

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ABSTRACT

The main risks of water supply in the Aegean Islands are (1) decreased water availability, (2) increased water demand, (3) degraded water quality, and (4) increased water losses in Water Supply Systems (WSS); these risk are due to impacts of Climate Change (CC) and direct human induced factors, including intensified tourism, inefficient irrigation practices, ageing infrastructure and inadequate water management. The water supply challenge in the Aegean Islands is how to effectively address these risks through management plans and targeted adaptation measures to reduce risks to acceptable levels. In the present work, literature and authors' experience are used to outline the key adaptations measures to face these risks. This description follows a typologized methodology that is based on the system of KTMs by Climate-ADAPT that defines 5 categories of measures. This system provides a standardized framework for communicating various adaptation measures and supporting adaptation policy processes across the EU. The adaptation measures are grouped in 5 categories: (1) Physical and technological measures, such as (1a) the design of infrastructure, such as WSS components considering CC impacts, (1b) the water loss control program to reduce water losses, (1c) more efficient irrigation practices (low-water-need/water-efficient crops, smart irrigation, and use of treated wastewater), and (1c) desalination systems using renewable energy sources, (2) nature based solutions and ecosystem-based approaches, such as (2a) rainwater harvesting systems, (2b) managed aquifer recharge, (2c) re-cultivation of terraced landscapes, and (2d) restoration of wetlands, (3) knowledge and behavioural change approaches, such as (i) good practices in the sector of tourism, e.g. reuse of treated wastewater for gardens and toilet flushing, and water scarcity reminders in hotel bathrooms, (ii) engagement of children and young people in projects, field trips and experiments on scarcity and proper water use, (iii) water-saving practices in households, such as the planting of drought-resistant vegetation, and (iv) pricing strategies that incentivize conservation, (4) governance and institutional measures, such as policy instruments, management and planning, and coordination, cooperation and networks, that (a) include Emergency Water Plans for droughts, e.g. water supply via mobile desalinations, and (b) ensure that all WSS components are adapted to CC, and (5) economic and finance measures, such as (i) incentive mechanisms and funding schemes, and (ii) insurance and risk sharing instruments, including Public-Private Partnerships mainly for the development of dams, wastewater reuse and desalination projects in the Aegean Islands. All measures should be examined and implemented holistically in WSS considering important links, such as the water-energy-food nexus concept.

Keywords: Water Stress, Water Supply, Aegean Islands, Climate Change, Adaptation Measures.

1. INTRODUCTION

The Aegean Islands are groups of Greek islands in the Aegean Sea that include (1) Sporades, (2) North Aegean Islands, (3) Evia, (4) Saronic Islands, (5) Cyclades, (6) Dodecanese, and (7) Crete. There are approximately 540 main islands; 200 of them are inhabited.

Water supply to the Aegean Islands is performed via the following methods:

- Surface waters from streams and springs that are collected in Reservoirs and Dams (R&D). There are R&D in the islands of Lemnos, Lesvos, Tinos, Mykonos, Ikaria, Serifos, Naxos, Ios, Patmos, Leros, Ios, Anafi, Astypalaia, and Crete [4]. In 2002 the total net water resources in the Aegean islands were estimated equal to approximately $1.25×10^9$ m^3/yr, 80% of which was surface waters and 20% groundwater [5]. According to the Approved River Basin Management Plans of the River Basin District (RBD) of the Aegean Islands (EL14) and Crete (EL13) issued in 2019: (i) the mean annual runoff for the Aegean Islands is estimated at $0.56 × 10^9$ m^3, and (ii) 9 D&R systems have been identified as lake type river HMWBs, while in the EL13 there are very significant D&R systems (e.g. Potamon, Aposelemi, Faneromenis, Plakiotissas and Mparmianon) that have been identified as HMWBs [6]. In 2024 some R&D systems, such as the Marathi dam (capacity = $3×10^6$ m^3) and the Ano Mera dam (capacity= $1x10^6$ m^3) were almost empty due to the prolonged drought, and were not being used, while in 2023 the two dams of Naxos had 30,000 m^3 that is equal to 8 % of their capacity (375,000 m^3) [7].
- Groundwater wells. Wells usually serve irrigation and livestock needs and account for 20-60% of the net water resources in the Aegean Islands [5]. Historically, groundwater has been extensively used in the Aegean islands for irrigation purposes, mainly in larger islands like Crete and Lesvos. Currently, wells in many islands were dried up (due to overextraction and increased needs) and became brackish (salinization) due to seawater intrusion [8].
- Import of potable water from the mainland to the islands via tanker ships. This method has been the most prominent method in the past decades that was subsidized for more than 20 years by the Greek Government and continues today; its cost is indeed very high and reached 12.77 EUR/m^3 for 2017 and 2018, while the transported water usually needs further treatment to achieve urban water quality standards and certainly it is not a permanent solution in scarce water conditions [1,2 and 3].
- Desalination plants that use mostly Reverse Osmosis (RO). According to Financial Times [9], in August 2024 there were 57 desalination units operating on the Aegean Islands alone, twice as many as a decade ago. Some islands such as Syros are entirely dependent on it, while others like Sifnos rely on it heavily. The cost of desalinated water in Greece ranges from 0.5 to 3.5 €/m^3; in small plants in the Aegean islands, it is higher than 1.2 €/m^3, while in large plants it is lower than 1 €/m^3 [3,10].
- Wastewater reuse. Reuse is currently practised on a very limited or pilot scale and indicative cases of wastewater reuse for irrigation purposes are (i) in Hersonissos (4500 m^3/d), Malia (2500 m^3/d) and Stalida in Crete for olive trees, and (ii) in Kos (3500 m^3/d) for olive and citrus trees [11,12, 13], while it is worth noting the pilot scale plants within the projects HYDROUSA in Lesvos [14] and RECREATE in Syros [15].
- Cisterns. Rainwater harvesting in tanks (cisterns) was a well-known practice from the Minoan Period (3300 BC) and some of these structures were constructed so well that worked for centuries and were used as the main source of water supply [16,17]. Nowadays, the Greek urban planning legislation imposes the construction of rainwater harvesting tanks in 27 islands of the Aegean [18]. Cisterns, which can also be underground, are characterized by (i) their limited capacity, (ii) dependence on rainfall and climate change, (iii) high water quality risks.

The climate in the Aegean Islands is predominantly Mediterranean, characterized by mild, wet winters and hot, dry summers. Temperatures in the Aegean region vary throughout the year; January tends to be the coolest month (average temperatures = 9 -12°C), while July and August are the warmest months (average temperatures up to 25-27°C). Precipitation varies significantly across the year peaking in winters (December) at around 171mm, while summers are incredibly dry, with minimal rainfall in July and August. There are up to 13 hours of sunshine per day [19].

Climate Change (CC) impacts are expected to affect significantly the Aegean islands, including water supply, agricultural production and the local economy. According to literature [20,21] eight climate hazards that are most frequently examined in Water Supply Systems (WSS) out of a broader set of 24 typologized hazards [22,23]. On islands, four additional coastal hazards need to be considered and the totally 12 hazards can be categorized into the following 5 groups:

- Mean air temperature increase (HC1) and extreme heat - heat waves (HC2).
- Mean precipitation decrease (WD1), aridity (WD4), droughts (WD5) and wildfires (WD6).

- Extreme precipitation (WD2) and flooding (WD3).
- Mean sea level rise (C1), coastal flooding (C2), erosion (C3) and saline intrusion (C4).
- Extreme winds (WA2).

The CC effects in the Mediterranean Region can be summarized as follows [24]:

- HC1 and HC2: Mean air temperature and its extremes will continue to increase more than the global average and heat waves to intensify in duration and peak temperatures,
- WD1, WD4, WD5 and WD6: Mean precipitation will decrease by 4–22%, droughts will become more severe, more frequent and longer and conditions will be drier, and large wildfires will increase,
- WD2 and WD3: Heavy precipitation and rainfall extremes will likely increase in the northern part of the Mediterranean region, potentially accompanied by an increase of flash floods,
- C1-C4: Sea level rise will increase enhancing the risk of coastal flooding, erosion and saline intrusion,
- WA2. Extreme winds intensity will increase.

The most widely studied impact of the above-mentioned climate hazards in the literature is the increased water stress in the Aegean Islands. According to the European Environment Agency [25], water stress occurs when the demand for water exceeds the available amount during a certain period or when poor quality restricts its use. Water stress causes deterioration of freshwater resources in terms of quantity (aquifer over-exploitation, dry rivers, etc.) and quality (eutrophication, organic matter pollution, saline intrusion, etc.). This paper deals only with water stress; however, there are also other (probably equally important) impacts, such as severe storms, floods, winds and wild fires, such as (i) the storm Bora in November-December 2024 in Rhodes and Lemnos (with torrential rainfall totalling 170mm in just 12 hours, powerful winds reaching speeds up to 130 km/h, resulting in two fatalities and infrastructure loss) [26], (ii) the flood in March-April 2025 in Mykonos and Paros that received at least a month's rainfall within three hours [27], and (iii) the wildfires in July 2023 in Rhodes where 19,000 people were forced to be evacuated from homes and tourist accommodation [28]; these effects should also be examined and faced in the Aegen Islands.

There are only a few research works in the literature on CC in the Aegean islands that mainly deal with the water stress in Aegean Islands and the related sectors, such as water supply, agriculture and tourism [29,30]. The main conclusions of these works, which typically involve projection of Regional Climate Models (RCMs) for various periods and CC scenarios to determine climate indicators, can be summarized as follows:

- Increased mean air temperatures and heat waves. Annual averaged maximum and minimum temperatures will increase by about 1.5 °C (RCP4.5) or 2.1 °C (RCP8.5) in the period 2031–2060 and almost 2.2 °C (RCP4.5) or 4.5 °C (RCP8.5) in the period 2071–2100. Hot days (days with $T_{max} > 30$ °C) and very hot days ($T_{max} > 35$ °C) will increase considerably, especially in the period 2071-2100. Hot days will be more frequent by 30–60 days/year (RCP4.5–RCP8.5), and very hot days by about 10–30 days/year (RCP4.5–RCP8.5) for the period 2071–2100 [30].
- Mean precipitation decrease and increased aridity and droughts. Total annual precipitation will decrease by 15–25% in the period 2071–2100, while increases in the maximum length of dry spells are projected. Under scenarios RCP4.5 and RCP8.5 they will last about 100 days, which is 20 days more than in the reference period 1971-2000 [30].

Subsequently, the four most important risks of WSS in the Aegean Islands, which are due to CC, but also to other hazards that can be often more important than CC, can be summarized as follows:

- Decreased water availability that is due to CC, whose effects can be direct, i.e. due to WD1, WD4 and WD5, and indirect, i.e. due to HC1 and HC2 [24].
- Increased water demand that is mainly due to increased tourism activities during summer months (including increased water used in swimming pools) and due to inefficient irrigation, and to a lesser extend due to direct or indirect effects due to climate hazards [24].
- Degraded groundwater water quality that is mainly due to saline intrusion (C4) [31].
- Increased Water Losses (WL) in WSS; these can be divided in categories as shown in Figure 1 [32]. Real losses (RL) are due to leakages (i) mainly of the Water Distribution Network (WDN) that are often triggered by factors, such as ageing infrastructure, wear and tear, suboptimal pressure management, and external interferences, such as road works or construction activities, but also due to CC effects [24], such as floods or earthquakes. Based on the audit report of the Hellenic Republic [33] issued in 2021 "the exact percentages of losses are (i) unknown, especially in cases of insufficient knowledge of the quantities of water entering the WDN, (ii) estimated approximately,

due to limited information on the volume of water produced and transported in the WDN from other sources, or (iii) remain at high levels. For example, in Chios, where a remote monitoring system is implemented to identify large leaks and efforts are made for targeted intervention by the operator, losses are estimated at approximately 43%, due to the age of the WDN or apparent losses. In Syros, despite the implementation of telemetry systems and the relatively new network, significant water losses exceeding 33% have been recorded, attributed to material failure according to the operator. In Santorini, the municipal company recorded a loss rate of 19% in the Oia area alone, which is considered relatively low from a comparative standpoint. According to [34], this figure is reported equal to 33-34%. Moreover, in the town of Skiathos, RL are estimated to range from 39% to 64% of the System Input Volume (SIV) in summer and winter, respectively, the corresponding Apparent Losses (AL) range from 9% to 2%, while the Unauthorized Consumption (UC) - water theft is estimated to be at least 3.6% [35].

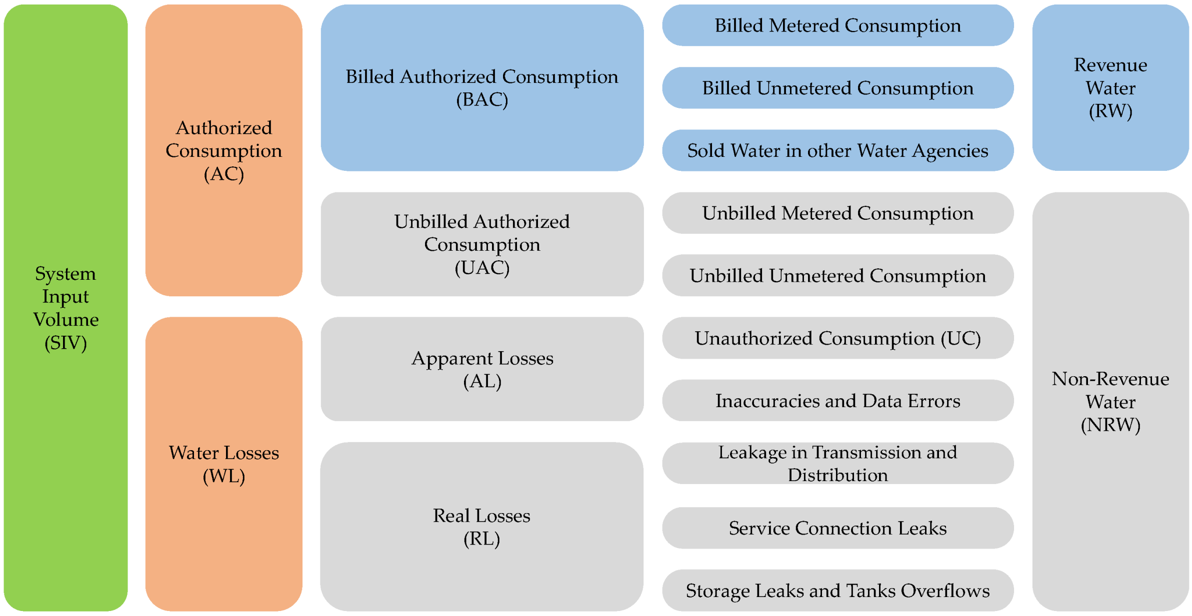

Figure 1: Categories of Water Losses [31].

The main water supply challenges in the Aegean Islands are how we can face the above-mentioned four risks effectively via risk management plans that involve a series of adaptation measures to reduce risks to acceptable levels or even to eliminate them.

In the present work literature and authors' experience are used to describe briefly the main adaptations measures to face these risks. It is noted that these measures should be examined and implemented in WSS following an integrated manner considering important links, such as the water-energy-food nexus concept [36]; this concept was applied in the project DarWEN by UNIVA, NTUA and MAS SA, whose main objective was to provide viable and secure energy and water supply solutions by developing and implementing an innovative, holistic and intelligent management system at community level that: (i) targets at the efficient operation of energy and water systems, (ii) favours the reduction of their operating costs and (iii) supports increased Renewable Energy Sources (RES) penetration rates and utilization at local level [37].

2. ADAPTATION MEASURES

2.1. Methodology

This work adopts a typologized methodology [22] that is based on the system of Key Type Measures (KTMs) by Climate-ADAPT. The KTM system was designed to document climate adaptation actions in the EEA member countries and thus to provide a standardized way of communicating various adaptation measures to better support adaptation policy processes across the EU [38], which defines the following categories of adaptation measures: (1) Physical and technological measures. (2) Nature Based Solutions and Ecosystem-based Approaches. (3) Knowledge and behavioural change approaches. (4) Governance and institutional measures. (5) Economic and Finance measures.

2.2. Physical and technological measures

Physical and Technological measures deal with (i) grey physical infrastructure, which can be new, rehabilitated, upgraded, or replaced) dated or (ii) technological options, such as Early Warning Systems, hazard / risk mapping and service / process applications.

The main grey infrastructure of WSS include [39]: (1) Water intake works to collect water, such as reservoirs and dams for surface waters, wells for groundwater, tanks for rainwater, and seawater intakes for desalination plants. (2) Water treatment works (i) for surface, groundwater and rainwater that generally include disinfection, coagulation-settling and filtration and (ii) desalination for seawater. (3) Storage works, such as tanks. (4) Water Distribution Networks (WDNs). (5) Buildings. (6) Supporting infrastructure, such as power supply, communications and control, transportation and access, and personnel.

Technological options include the following:

(1) TEC1 Design of WSS taking into account climate change. All components of a WSS should be designed considering CC and following an integrated master plan, for example (i) using the Water-Energy Nexus (integration of water supply problem with the energy problem [40], (ii) considering not only ephemeral needs, such as tourism, but also basic and vital needs, such as agriculture. Doorga et al. [41] proposed the construction of mini dams and off-channel mini reservoirs near water stress areas to mitigate the impacts of declining rainfall and rising demand, ensuring a more resilient WSS for Mauritius via capturing water lost to the sea, increasing the water stock capacity by 0.5 Mm^3.

(2) TEC2 Water Loss Control Program to reduce water losses. In 1996 the Operation and Maintenance Committee of the IWA's Distribution Division set up a Task Force to review existing methodologies for international comparisons of Water Losses from WSS aiming at (i) the preparation of a recommended basic standard terminology for the calculation of real and apparent losses, and (ii) the review and recommended preferred performance indicators for international comparisons of losses [31]. In 2013 EPA presented a Water Loss Control Program that consists of the following steps: (i) water audit that identifies and quantifies the water uses and losses from a water system, (ii) intervention that addresses the findings of the water audit through implementation of controls to reduce or eliminate water losses, and (iii) evaluation that uses performance indicators to determine the success of the chosen intervention actions [42]. In Greece, Karagiannis presented the proposed best practices and strategic actions for the management of the Non-Revenue Water (NRW) in EYDAP SA [43].

(3) TEC3 More efficient irrigation practices, that include (i) the promotion of low-water-need/water-efficient crops, (ii) the improvement of irrigation networks ensuring that the water required for plant growth is delivered to the soil in a controlled manner, such as smart irrigation that optimizes water usage, enhances yields, and supports sustainability via the integration of Information and Communication Technologies (ICT), Artificial Intelligence (AI) and the Internet of Things (IoT), and (iii) Best Management Practices (BMPs). For example, Liopa-Tsakalidi et al. [44] presented a LoRaWAN-based prototype drip irrigation platform that was implemented in a 22-hectare olive grove in Greece that monitors soil moisture levels using IoT end nodes with low-cost microcontrollers and embedded sensors; with this system water consumption was reduced by 42 % in 2020 and 25 % in 2021. Udias et al. [45] applied a decision support tool that integrates (i) the SWAT model, (ii) an economic model, and (iii) multi-objective optimization to identify and locate optimal irrigation strategies, and concluded that (i) water irrigation volumes could be reduced by 32%-70% while preserving current agricultural benefit, and (ii) an optimal reallocation of water could reduce irrigation water volumes by 52% at the cost of a 7% loss of agricultural income, but maintaining the current agricultural benefit. The use of treated wastewater can also be considered as environmentally smart irrigation method, because (i) it does not require water from the WSS, (ii) it does not require the addition of nutrients (fertilizers) and (iii) it applies the principle of circular economy via the transformation of "wastewater" to "water resource". However, this method can be more expensive, because (i) it often requires additional (tertiary) treatment using mainly grey infrastructure and sometimes NBS, and (ii) it needs to be accepted by the local farmers and residents.

(4) TEC4 Desalination systems using Renewable Energy Sources (RES). Kyriakarakos and Papadakis [2] investigated combinations of small-scale RO desalination systems that produce up to a few thousand m^3 of desalinated water per day coupled with photovoltaic (PV) and wind energy systems (in grid-connected and in autonomous scenarios) and concluded that RO desalination using RES (i) can address cost-effectively the current issues in terms of water scarcity, while minimizing the environmental footprint of the process, (ii) can be deployed in practically any location on earth having access to sea or a brackish water source and (iii) are more cost-effective and profitable than without RES even for grid-connected systems, apart from the corresponding environmental benefits. Kourtis et al. [46] examined five different water resource management scenarios on eight dry islands of the Aegean Sea; the first scenario employed current water supply practices combined with domestic rainwater harvesting systems, while the rest scenarios involved desalination using wind-power. The authors argued that wind-powered desalination can be combined with rainwater harvesting as a supplementary source of water and/or seawater pumping and an additional source of energy, evaluated all scenarios for a 30-year lifespan and proposed an optimal solution for each island based on a Life Cycle Cost (LCC) analysis.

2.3. Nature Based Solutions and Ecosystem-based approaches

Nature Based Solutions (NBS) and Ecosystem-Based Approaches (EBA) include green and blue options, such as the following:

(1) NBS1 Rainwater Harvesting Systems (RHS). RHS consists of the collection, storage (usually in tanks) and treatment of rainwater from rooftops, terraces, courtyards, and other impervious building surfaces for on-site potable uses, such as drinking and cooking, and non-potable uses, such as laundry, garden irrigation, terrace cleaning, toilet flushing, and other external usages. The aims of RHS are to (i) alleviate the consumption of water from primary water supply sources, (ii) reduce energy consumption required for pumping/transportation of water from central water supply systems to end-users, and (iii) decrease stormwater runoff conveyed to urban drainage systems [47]. Feloni and Nastos [48] simulated RWH systems (rooftop collection area: 40-140 m^2, rainwater tank volume: 5-30 m^3, number of household members: 2-3, coverage: 54 L/d) under CC scenarios in Fourni and Nisyros to (i) underscore the potential of RWH systems as a cost-effective “green” solution, particularly in regions with deficient rainfall regimes, and (ii) highlight the importance of localized water management strategies. The RWH programme in Greece by the Non-Conventional Water Resources (NCWR) that was applied in 33 Aegean Islands [49] aimed at revitalising and reintroducing traditional RHS combined with innovative techniques and methods in the Greek islands, as a tool to improve water availability and CC adaptation at a local level. The programme activities included: (i) installation of new and reinstatement of existing RHS in selected public buildings and areas across its areas of operation, (ii) pilot installation of a greywater recycling system and three water kiosks, (iii) demo installation of a green wall and upgrade of a swimming pool, (iv) water saving activities through the distribution of water saving kits to households in water-scarce islands, (v) awareness raising and dissemination of Programme results through targeted events and/or conferences, and (vi) educational and training activities.

(2) NBS2 Managed Aquifer Recharge (MAR). MAR is used to (i) prevent groundwater storage and provide water supply resilience, (ii) improve groundwater quality, (iii) mitigate saltwater intrusion, (iv) convey stormwater from collection areas, and (v) reduce flood risk. MAR systems include the following techniques: (i) spreading methods like infiltration ponds that allow water to seep into the aquifer, (ii) induced riverbank filtration that involves extracting groundwater from wells near rivers or lakes to improve water quality, (iii) in-channel modifications, such as sand dams that retain water, and (iv) recharge wells or boreholes that inject water directly into aquifers. Water sources involve (i) surface water, (ii) tertiary treated wastewater and (iii) captured water, including stormwater, floodwater, and urban irrigation runoff [50].

(3) NBS3 Re-cultivation of terraced landscapes (TERL). Re-cultivation of terraced landscapes (TERL). TERL can be used for infiltration, erosion control to slow runoff and increase water retention in soils, also aiding groundwater recharge. Sakellariou et al. [51] presented a case study of abandoned terrace re-cultivation in Andros using a climate smart agriculture system, which involves the establishment of an extensive meteorological network to monitor the local climate and hydrometeorological forecasting. Along with terrace site mapping and soil profiling the performance of cereal and legume crops was assessed in a low-input agriculture system.

(4) NBS4 Restoration of wetlands. Wetlands act as natural water filters and reservoirs; they contribute in (i) recharging groundwater, (ii) maintaining water quality, (iii) regulating water flow in rivers and streams, (iv) buffering floodwaters during floods, absorbing excess water and reducing flood risks in surrounding area, and (v) ensuring steady water supply during dry seasons, benefiting both humans and wildlife [52]. There are 500 wetlands on 57 islands of the Aegean Sea. The largest wetlands are found in Limnos, Evia, Naxos (the largest wetland of the Cyclades complex) and Kos (the largest of the Dodecanese complex), while in Lesvos alone, there are 85 wetlands [53].

2.4. Knowledge and Behavioural change approaches

Knowledge and Behavioural change approaches include [38]: (1) Information and awareness raising, such as research and innovation, communication and dissemination and decision support tools and databases, and (2) identification and sharing of good practices, training, and knowledge transfer, and reporting on lifestyle practices and behaviours.

Research and innovation include demonstration projects, such as the sites of (i) HYDROUSA [14] at full scale in Lesvos, Mykonos and Tinos, and (ii) CARDIMED [54] at Lesvos, Mykonos and Sifnos.

For communication and dissemination various tools and channels can be used, such as (i) printed material that are based on research projects (e.g. publications, fact sheets, posters, leaflets and heritage booklets), mainly for schools, universities, municipal offices, policymakers, NGOs and hotels [14,54], (ii) visual & multimedia (e.g. videos, visual tours, animations and photography exhibitions), (iii) digital and online tools (e.g. websites and portals that include case studies and educational content, social media, apps and webinars), (iv) community participation and engagement means (e.g. workshops, public forums, and school projects), and (v) traditional media.

Indicative decision-support tools and databases, which are mostly used by researchers, planners, farmers and hotels, are (i) the WaPOR portal by the Food and Agriculture Organization of the United Nations that is a publicly accessible, near real time database using satellite data that allows the monitoring of agricultural water productivity [55], and (ii) the European & Global Drought Observatories of Copernicus reporting the situation of Combined Drought Indicator in Europe [56].

Behavioural Change Approaches include the promotion of (i) good practices in the sector of tourism, e.g. reuse of treated wastewater for gardens and toilet flushing, and reminder stickers in bathrooms on water scarcity in hotels, (ii) the engagement of children and young people in projects, field trips and experiments on scarcity and proper water use, (iii) water-saving practices in households, such as the use of RHS and the planting of drought-resistant vegetation, (iv) pricing strategies that reward low water consumption and penalize the waste of water, such tiered water tariffs and subsidies for installing water-saving devices, and (v) the collective responsibility of the members of the community for shared (and often traditional) water sources, such as cisterns or reservoirs.

2.5. Governance and institutional measures

There are various governance and institutional measures that include: (i) policy instruments, (ii) management and planning, and (iii) coordination, cooperation and networks. These measures should be applied (i) ensuring the coordination across sectors and levels via the creation of water committees, enforcement of regulations, and the involvement of local communities, (ii) involving Emergency Water Plans for droughts and other hazards, such as storms or contamination events via emergency water supplies including mobile desalination units, (iii) ensuring that all water infrastructure components are adapted to CC [21, 23 and 24].

There are various governance and institutional measures in Greece on water management that include EU Directives, such as the WFD. Recently, very important measures that are related to the water stress and scarcity in the Aegean Islands, were announced. In August 2024 the Greek Government announced that €11.25 million will be provided within the framework of the Development Program of the Ministry of Interior to support the municipalities, the Municipal Water Supply and Sewerage Enterprises (DEYA) and the Water Supply and Sewerage Associations to implement immediate actions to tackle water scarcity than include: (i) drilling of new or upgrading of existing water supply boreholes, and (ii) desalinated water supply service through the rental of desalination systems. Each potential beneficiary is entitled to submit one proposal up to the amount of 150000 euros. It is clarified that the municipalities of the Regions of the Ionian Islands, South Aegean and North Aegean, which are excluded from this call, will be financed by a corresponding action of the Ministry of Shipping and Island Policy [57]. In June 2025 the Greek Government announced a major reform to tackle water scarcity, whose main points are the following: (i) the sum of €10 billion will be invested in water supply and irrigation projects focusing on several high-risk regions, including the Aegean Islands, while it is noted that funding such large-scale projects requires creditworthy entities that can attract financing. The European Investment Bank (EIB) is expected to be a key partner, potentially providing up to €3 billion annually for qualified water management projects, The main points of this reform are the following: (i) the government is considering the creation of 45 new corporate public entities, and (ii) water prices are expected to rise potentially exceeding EU averages in some regions [58]. In July 2025 the Greek Government launched its 30-Year National Water Strategy to address increasing water scarcity and long-term climate challenges, which is designed to modernize how Greece produces, distributes, and conserves water. The main pillars of this strategy are: (i) affirming water as a public good in line with the Constitution, (ii) ensuring financially viable water, irrigation, and sewage services with fair pricing, (iii) centralized planning and management of large- and small-scale projects, (iv) immediate short-term actions over the next six months, supported by a public awareness campaign, and (v) adoption of new technologies, including recycling, reuse, and desalination [59]. In August 2025 the Ministry of Shipping and the General Secretariat of the Aegean and Island Policy (GSAIP) proceeded with the implementation of water sufficiency and desalination projects, with emphasis on the most remote and small islands. The programme includes 103 interventions in 61 island municipalities (OTAs) and DEYAs, with funding of €9.1 million from the Public Investment Programme, as part of the Special Action Plan for Water Scarcity for the year 2025. Moreover, in cooperation with the Ministry of Environment and Energy an additional funding of €20 million was approved for projects in areas of immediate need. The main points of this program are: (i) licensing of small desalination plants will be simplified using fast-track procedures, (ii) the GSAIP is providing technical support to small island municipalities and undertaking the tender procedures to avoid delays, and (iii) cooperation is underway with the Ministries of Environment and Energy, Interior and Economy and Finance, aiming at (i) developing standard specification sheets, (ii) establishing uniform costing for desalination projects and (iii) supporting weak beneficiaries [60].

Pools are significant water consumers accounting for up to ~6% of total water consumption in tourist-heavy islands, such as Paros and Mykonos. There are various policy measures that can be applied to reduce water consumption in pools, such as (i) legislation allowing hotel pools to be filled with seawater subject to proper licensing and regulations that ensure (a) the good quality of used water (via for example dichlorination), and (b) no aesthetic impacts due to the discharge of used water, and (ii) imposing taxes on pool owners that will be directed to infrastructure and other works against water stress [61].

2.6. Economic and Finance measures

Economic and finance measures include: (i) financing and incentive instruments, e.g. incentive mechanisms and funding schemes, and (ii) insurance and risk sharing instruments, e.g. insurance schemes and products, and contingency funds for emergencies; the measures described in 2.5 include also economic measures. Furthermore, one of the most important insurance instruments is the Commission Decision of 7 December 2011 concerning compensation payments made by the Greek Agricultural Insurance Organisation (ELGA) in 2008 and 2009 [62].

On the Public-Private Partnerships (PPP) unit of the website of the Ministry of Economy and finance [63], it is stated that PPPs "constitute an important reform in the field of infrastructure creation and the provision of public services. Constituting a pillar of a new development model, they contribute significantly to the development of the Greek economy, enhancing the effectiveness and efficiency of Public Sector resources". The World Bank describes PPPs and their benefits [64]. Up to now, the list of PPPs projects in the sector "Water-Environment" contains only 2 projects in Crete (for irrigation or/and water supply). The number of PPPs is expected to increase, mainly for the development of dams, wastewater reuse and desalination projects, in the Aegean Islands; however, attention should be paid so that the cost of water for the municipalities is affordable.

3. CONCLUSIONS

The following adaptation measures were presented to face the risks of water supply in the Aegean Islands: (1) Physical and technological measures, such as (1a) the design of grey infrastructure considering CC, (1b) the water loss control program, (1c) more efficient irrigation practices, and (1c) desalination systems using renewable energy sources, (2) nature based solutions and ecosystem-based approaches, such as (2a) rainwater harvesting systems, (2b) managed aquifer recharge, (2c) re-cultivation of terraced landscapes, and (2d) restoration of wetlands, (3) knowledge and behavioural change approaches, such as (i) good practices in the sector of tourism, (ii) engagement of children and young people in projects, field trips and experiments on scarcity and proper water use, (iii) water-saving practices in households, and (iv) pricing strategies, (4) governance and institutional measures, such as policy instruments, management and planning, and coordination, cooperation and networks, that (a) include Emergency Water Plans for droughts, e.g. emergency water supplies via mobile desalination units, and (b) ensure that all WSS components are adapted to CC, and (5) economic and finance measures, such as incentive mechanisms and funding schemes, and (ii) insurance and risk sharing instruments, including Public-Private Partnerships mainly for the development of dams, wastewater reuse and desalination projects in the Aegean Islands. All measures should be examined holistically in WSS following an integrated manner considering important links, such as the water-energy-food nexus concept.

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MEDIUM-TERM PROBABILISTIC WIND ENERGY FORECASTING BASED ON SEASONAL CLIMATE DATA: INSIGHTS FROM A SUBSTATION-LEVEL APPLICATION

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ABSTRACT

Medium-term wind energy forecasting, spanning time scales from days to several months, is essential for optimizing the integration of wind farms into electricity generation. This optimization further leverages the advantages of renewable energy resources, including a reduced environmental footprint and greater energy independence, which are directly related to lower price volatility in energy markets and consequently reduce exposure to potential energy supply crises.

Accurate forecasts are critical for coordinating generation and ensuring effective participation of RES-based technologies in modern energy markets. Integration challenges become increasingly pronounced in power systems characterized by high renewable penetration, low system inertia, and limited storage capacity. This growing complexity amplifies the need for reliable medium-term forecasts that help system operators manage variability and uncertainty, thereby mitigating integration challenges and enabling more flexible and resilient system operation.

Wind energy production is inherently variable and highly dependent on local weather conditions, underscoring the need for advanced forecasting methods. This study presents a novel methodology that employs an ensemble of seasonal climate forecasts to predict medium-term aggregated wind energy production. The approach combines meteorological predictions with the technical characteristics of wind turbines and historical wind speed data, generating probabilistic output estimates that can be further exploited to quantify and constrain forecast uncertainty.

The methodology was applied to the Greek National Interconnected System, focusing on a particular substation located in South Euboea. The substation aggregates the production of 61 wind turbines registered across four wind parks. The objective was to assess the approach in a real-world application context. Over a 42-month testing period, using seven distinct seasonal forecast datasets, the method demonstrated a mean absolute percentage error below 17%. Additionally, it generated actionable operational signals, such as a lowest guaranteed energy production level. These findings underscore the value of leveraging seasonal climate forecasts for medium-term wind energy prediction, providing tools that directly support operational decision-making and can be incorporated into advanced forecasting frameworks.

Keywords: Renewable Energy Integration; Seasonal Probabilistic Energy Forecasts; Forecasting Error Analysis; Case Study

1.INTRODUCTION

The value of medium-term wind energy forecasting lies in its ability to enhance coordination across generation resources, streamline maintenance planning, improve resource management, and enable effective participation in energy markets, functions that become increasingly vital for power systems operating with high shares of renewables, reduced inertia, and constrained storage capacity.

Wind energy production exhibits significant variability and is highly dependent on local weather conditions, making medium-term forecasting a challenging task. This underscores the need for advanced, reliable forecasting tools to inform both operational and economic decision-making.

To develop such tools, a variety of approaches are employed, targeting either direct forecasting of energy production or key meteorological variables such as wind speed and direction. Physical weather and seasonal climate models are commonly used to produce wind speed forecasts, which are then converted to energy forecasts, often through statistical methods. Concurrently, alternative approaches leverage statistical theory and artificial intelligence to harness local historical data for forecasting purposes. Hybrid methodologies that combine these techniques have demonstrated superior performance [1].

Forecasts based on climate models typically focus on key variables such as wind speed and direction; however, their seasonal prediction accuracy can be affected by shifts in atmospheric patterns, partly driven by climate change. To account for inherent uncertainties, such forecasts are often presented in probabilistic form, which can be further leveraged to enhance forecasting capabilities.

This paper presents a methodology for generating medium-term wind energy production forecasts based on probabilistic seasonal forecasts of wind speed. Applied at the substation level within the Greek National Interconnected System (NIS), this approach enables the assessment of forecasting capabilities to produce accurate predictions and actionable operational signals, such as the lowest guaranteed energy production level and probability-based risk assessments. The assessment also provides valuable insights into whether these signals can be effectively used to directly support informed operational decision-making, as well as their potential for integration into advanced forecasting frameworks.

2.METHODOLOGY

The medium-term forecasts of wind energy production rely on seasonal forecasts of wind speed. These wind speed forecasts are generated using forecasting systems, that provide at least sub-daily outputs at 6-hour intervals (i.e., at 00:00, 06:00, 12:00, and 18:00) and extends up to seven months from the issuance date, in a gridded format. The methodology follows these key steps:

1. Collection of geospatial data and design parameters of the wind turbines (WTs) and wind farms (WFs) under study.
2. Spatial alignment of wind resource forecasts and the locations of the WTs.
3. Vertical extrapolation of wind speed values from each member of the seasonal forecast ensemble to the hub height of every WT.
4. Estimation of the Weibull distribution parameters (k and C) of monthly wind speeds for each unique combination of location, hub height, and ensemble member.
5. Calculation of energy production of each wind turbine and for each ensemble member, based on the derived Weibull distributions.

After the application of the forecasting methodology, the evaluation of forecast skill is performed in order to assess the reliability of the predicted wind energy production. The assessment is carried out in two key steps:

1. Collection of operational data —measurements of energy production— from WFs, individual WTs, and/or associated grid substations.
2. Comparison of the forecasts with the operational data over the same time period.

The proposed methodology is applied in NIS, at a substation level, and the corresponding process flow is illustrated in Figure 1, which incorporates images from [2], [3], [4], and [5].

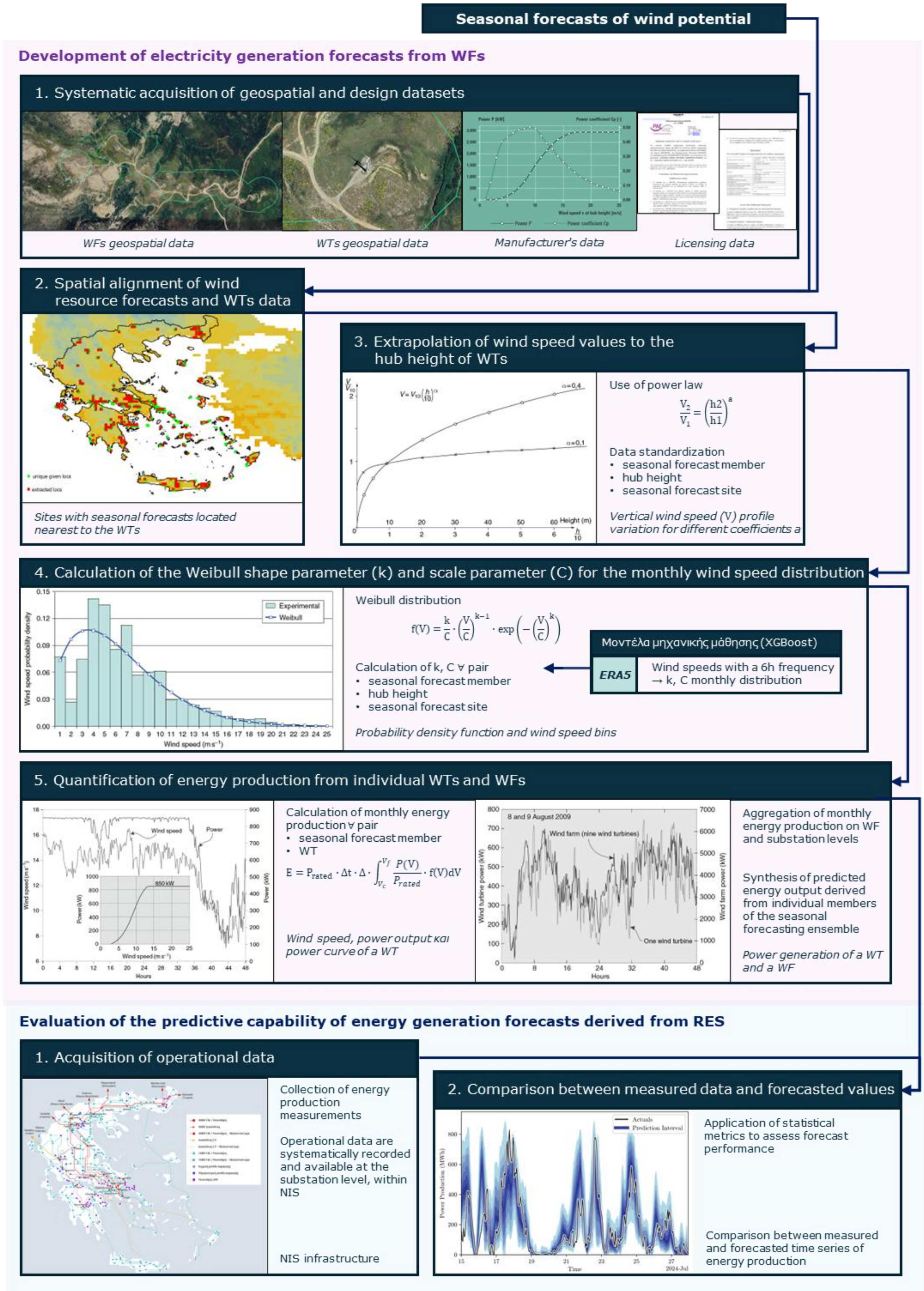

Figure 1: Flow diagram of the methodology for medium-term wind energy production forecasts, covering both forecast generation and evaluation.

2.1 Collection of geospatial data and design parameters of WTs

The minimal geospatial inputs necessary for the implementation of the proposed methodology include the point-form geographical coordinates (latitude and longitude) of the WTs. The corresponding elevation may be extracted from the given coordinates if it is not explicitly available.

Furthermore, for the WTs examined, including those with operating licenses, a fundamental set of manufacturer specifications is necessary. Each WT should have a power curve correlating wind speed with power generation. Should these curves be unavailable, the use of typical power curves is deemed acceptable, particularly when the study is conducted at a regional scale.

2.2 Spatial alignment of wind resource forecast grid points and WTs locations

Most seasonal forecasting systems offer a broad set of meteorological variables that can be leveraged for wind energy production forecasting. This methodology focuses on wind speed, which is supplied as gridded data. In the current study, a higher spatial resolution of 9×9 km is used, though the methodology remains applicable irrespective of the spatial resolution of seasonal wind speed forecasts, noting that lower resolution (fewer grid points) generally leads to diminished forecast performance.

In practice, the coordinates of the seasonal wind speed forecasts differ from those of the WTs. To overcome these spatial inconsistencies, various approaches may be employed, including fluid dynamics models, statistical techniques, geospatial interpolation methods, machine learning algorithms, or a hybrid combination thereof [1]. In the context of the proposed methodology, wind speed forecasts corresponding to the nearest grid points to each WT were utilized. This strategy enables the seamless application of grids with differing spatial resolutions without requiring manual intervention or adjustments.

2.3 Vertical extrapolation of wind speed values

The seasonal wind speed forecasts, typically produced by Numerical Weather Prediction (NWP) models, are provided at a height, which does not correspond to the hub height of the studied wind turbines, which is in turn required for accurately applying wind power curves in energy production calculations. Consequently, wind speed values were extrapolated to the hub height for each wind turbine. To do so, several methodologies have been developed [6], [7], [8], [9], [10].

In the context of applying the proposed methodology, the power law (also known as the Hellman equation) is used to extrapolate wind speed values [2], [11], as shown in Equation (1).

$$\frac{\boldsymbol{V_2}}{\boldsymbol{V_1}} = \left(\frac{\boldsymbol{h_2}}{\boldsymbol{h_1}}\right)^{\boldsymbol{a}} \quad \textbf{(1)}$$

Where

- V_1, the wind speed at height h_1.
- V_2, the wind speed at height h_2.
- a, an exponent that is strongly influenced by the topography and the stability conditions of the atmospheric layer near the ground.

2.4 Estimation of the Weibull distribution parameters (k and C)

The wind speed histogram of a region is often reasonably well described by the Weibull distribution. The Weibull distribution is a continuous probability distribution named after Waloddi Weibull, who provided a detailed description of it in 1951 [12]. The probability density function of this distribution depends on the parameters k and C, as shown in Equation (2).

$$\boldsymbol{f(V) = \frac{k}{C} \cdot \left(\frac{V}{C}\right)^{k-1} \cdot exp\left(-\left(\frac{V}{C}\right)^{k}\right)} \quad \textbf{(2)}$$

Where

- $f(V)$, the probability density function.
- V, the wind speed.
- C, the shape parameter.

- k the scale parameter.

The parameter C is a measure of the mean wind speed in the study area. Therefore, higher values of this parameter indicate a higher average wind speed, and vice versa.

The parameter k is a measure of the variability of the wind speed. Lower values of this parameter indicate greater dispersion of wind speed values, and vice versa. Consequently, smaller values of k correspond to a flatter distribution curve.

Seasonal forecasts of meteorological parameters often have low temporal resolution. In particular, wind speed is typically provided as instantaneous values every 6 hours (sub-daily), specifically at 00:00, 06:00, 12:00, and 18:00 each day.

Since the present methodology aims to forecast monthly energy production, it is necessary to describe the wind potential using the Weibull distribution on a monthly basis. The number of forecasts per month ranges from a minimum of 112 to a maximum of 124. However, this number of wind speed forecasts per month is considered insufficient to adequately describe the wind potential.

Acknowledging the above, the following process has been devised to compute the parameters of the monthly distribution using data with lower temporal resolution:

1. Collection of hourly wind speed data. A variety of models or observational datasets spanning different time periods may be utilized. In this study, the ERA5-Reanalysis model is employed, which offers hourly wind speed values corresponding to the same locations as the forecasted wind speeds.
2. Spatial alignment of the hourly wind speeds with the WTs location, based on proximity.
3. Vertical extrapolation of the hourly wind speeds from 10 meters, i.e. the reference height in ERA5-Reanalysis wind speed forecasts, to the hub height of each WT using the power law. In this particular study, a constant exponent is used (i.e. $\alpha = 0.14$).
4. Calculation of the parameters k and C based on the hourly wind speeds. These parameters are computed for each unique wind speed location and WT hub height. Specifically, the parameters are estimated from the ERA5-Reanalysis hourly wind speeds using the Maximum Likelihood Estimation method. For this purpose, relevant algorithms were developed based on the library [13]. This method estimates the values of k and C that maximize the likelihood function by fitting the Weibull probability density function to the hourly wind speed data. The parameters are calculated separately for each unique combination of geographic location and hub height to reduce computational load.
5. Training of a machine learning model based on the eXtreme Gradient Boosting (XGBoost) technique for each unique location, hub height, and month pair. To do so, custom algorithms were developed using the XGBoost library [14] to train the model.
6. Calculation of the parameters k and C for each unique location and hub height pair, using the trained models and the low temporal resolution wind speed forecasts.

2.5 Calculation of energy production based on the Weibull distribution

Energy production can be calculated using Equation (3).

$$\mathbf{E} = \mathbf{P_{rated}} \cdot \mathbf{\Delta t} \cdot \mathbf{\Delta} \cdot \int_{V_c}^{V_f} \frac{\boldsymbol{P(V)}}{\boldsymbol{P_{rated}}} \cdot \mathbf{f(V)dV} \quad \textbf{(3)}$$

Where

- E, the monthly energy production.
- P_{rated}, the nominal power output of the WT.
- Δt, the time duration of the given month.
- Δ, the technical availability of a WT.
- $f(V)$, the probability density function of forecasted wind speeds (see also §2.4).
- V, the wind speed.

- V_c, the cut-in wind speed of the given WT.
- V_f, the cut-out wind speed of the given WT.
- $P(V)$, the power curve of the given WT.

In many cases, wind turbines are installed with a rated power exceeding the limit allowed by their operational permits. In this context, the maximum power they can produce is restricted by appropriately modifying the turbine's power curve.

Seasonal forecasting systems often comprise multiple ensemble members. Calculating energy production for each unique ensemble member – WT pair preserves the probabilistic nature of the analysis, albeit at the cost of increased computational and data storage demands.

2.6 Evaluation of forecasting skill

For the evaluation of forecasting skill, the first step is to collect energy production measurements corresponding to the forecasted time period. These measurements are essential for assessing forecasting performance, while also providing added value by enabling the development or improvement of data-driven forecasting models.

Such measurements are typically collected from private producers, electricity grid operators, energy exchanges, and relevant regulatory authorities such as the Regulatory Authority for Energy, Waste and Water (RAAEY). However, they are rarely available for research purposes. Within the framework of the present study, data were collected at the substation level of the electrical grid through Independent Power Transmission Operator (IPTO).

Moreover, design data are required to associate WTs with the substations to which they are connected. This information can be obtained from the grid operator, which is IPTO in the case of NIS, and matching can be performed using the corresponding application numbers. It should be noted that, since the data originate from different registries, standardization is necessary to enable meaningful comparisons, a process that is often complex and resource intensive.

The second step in forecasting skill evaluation is the comparison of forecasts with the measured energy production over a time period. The data are in the form of time series and are compared using the statistical metrics of Table 2 [15], [16]:

Table 1: Evaluation metrics.

Metric	Equation	Description
MAE	$\frac{1}{n}\sum_{i=1}^{n}\lvert y_i - \hat{y}_i\rvert$	The metric has the same units as the measured quantity. A lower value of the metric indicates better forecasting skill.
RMSE	$\sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}$	The metric has the same units as the measured quantity and places greater emphasis on larger errors compared to the MAE metric. A lower value of the metric indicates better forecasting skill.
MAPE	$\frac{1}{n}\sum_{i=1}^{n}\frac{\lvert y_i - \hat{y}_i\rvert}{y_i} \cdot 100\%$	The metric is expressed as a percentage and can take large values in cases where the error is small, but the measured values themselves are very low. A lower value of the metric indicates better forecasting skill.
WAPE	$\frac{\sum_{t=1}^{n}\lvert y_i - \hat{y}_i\rvert}{\sum_{t=1}^{n}\lvert y_i\rvert}$	The metric is expressed as a percentage and does not account for the specific characteristics of the MAPE metric. A lower value of the metric indicates better forecasting skill.
Where i, is the sample number, n, is the sample size, y_i is the forecasted value, y^i is the measurement, and $\bar{y}$ is the mean of the measurements.		

3.APPLICATION

The proposed methodology is developed and applied within the research program CLIMPACT (https://climpact.gr/main/) for all 328 WFs connected to NIS with valid operating permits. These WFs consist of a total of 2,661 wind turbines, as illustrated in Figure 2. This paper specifically focuses on the Paradeisi substation, located in south Euboea at 450m, within the region of Central Greece, which hosts nearly 40% of the total number of licensed WTs. At the time of the study, four WFs were connected to the Paradeisi substation (based on 2022 connection offers). These WFs collectively comprise 61 WTs with a total licensed capacity of 72.4 MW. The infrastructure in south Euboea is shown in Figure 3, with the Paradeisi substation highlighted inside a box.

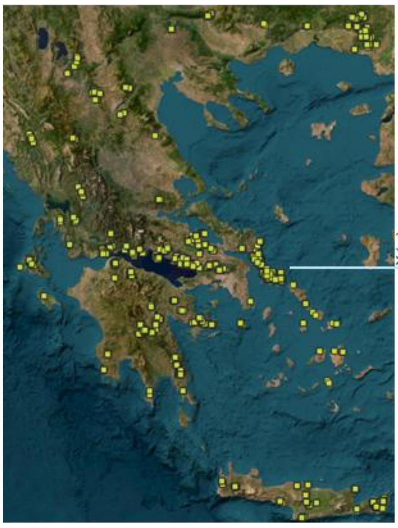

Figure 2. WTs in Greek NIS

Figure 3. The south Euboea substations, WTs, WFs and mean values of wind speed forecasts for January 2022 of the 20th ensemble member

4.RESULTS

The forecasting skill is evaluated over the period from July 2019 to December 2022. Seasonal forecasts of wind speed are produced, by 51 ensemble members, twice yearly, prior to June and December, providing forecasts for seven and six months ahead, respectively. Figure 4 shows the forecast initialization dates, the measured monthly energy production at the Paradeisi substation, and the corresponding statistical summary of the energy production forecasts in the present work, for the four wind farms and 51 ensemble members of the seasonal forecasting system. The statistics include the minimum, maximum, 25th to 75th percentile quartiles (Q1 and Q3) and the median.

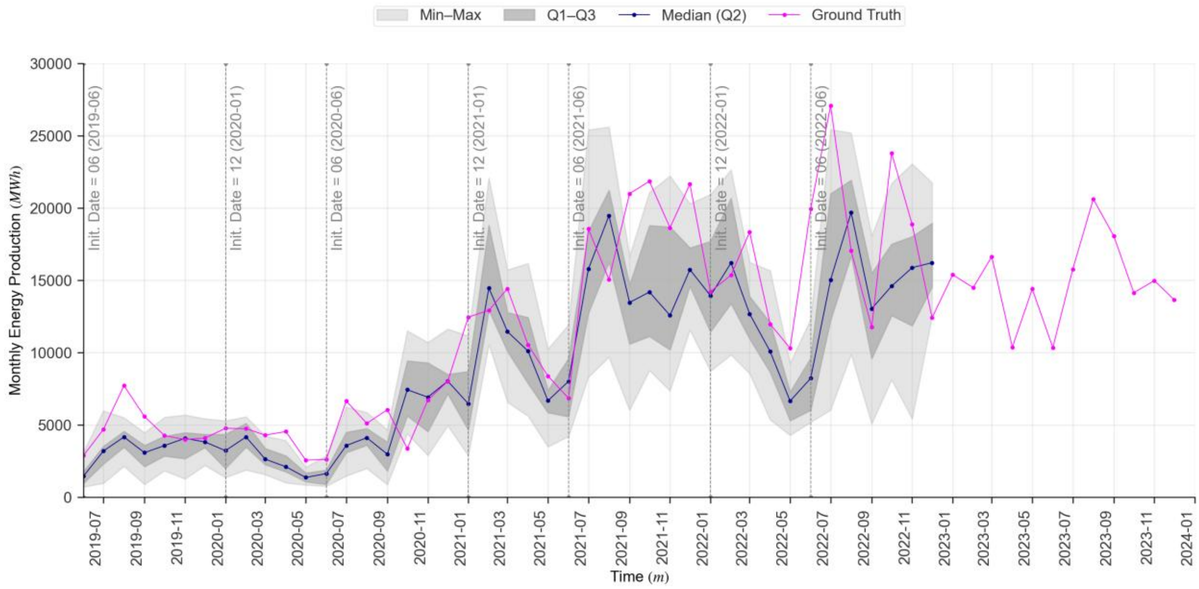

Figure 4: The forecast of monthly energy production at the Paradeisi substation, along with its statistical characteristics across 51 ensemble members and the corresponding observations

4.1 Monthly forecast error analysis

Figure 5 shows the error calculated using four statistical metrics for each month separately, along with the ensemble member that achieves the smallest error (indicated above each bar). No consistent pattern of increasing error is observed, except for a slight rise near each September. Additionally, considerable variation in error is evident across different months.

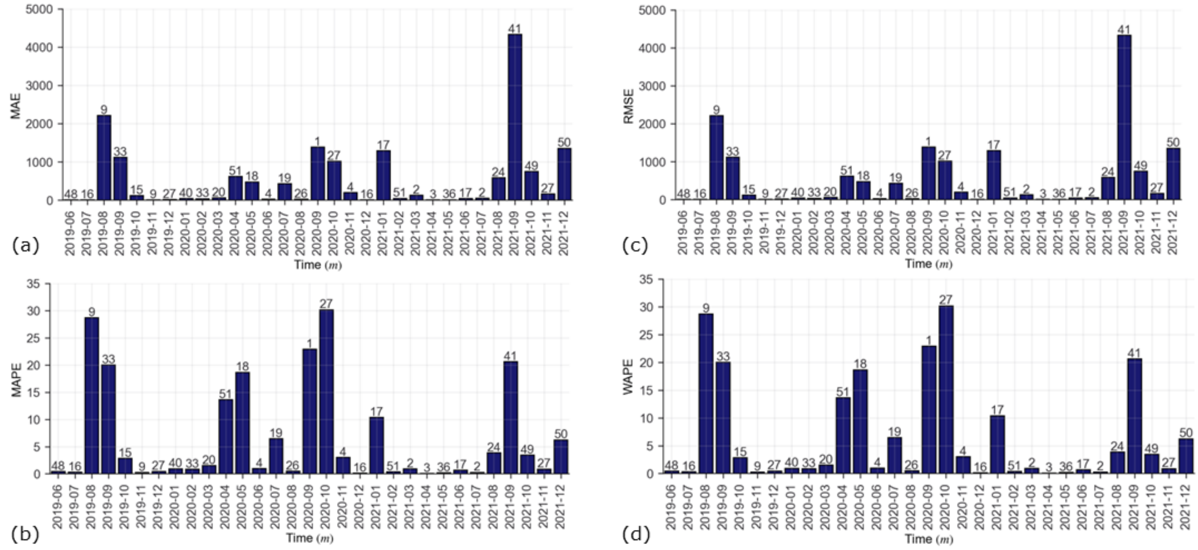

Figure 5: The ensemble member and the minimum error of MAE, RMSE, MAPE, and WAPE in the energy production forecast for each month separately, from June 2019 to December 2022

4.2 Guaranteed energy production

Medium-term wind energy production forecasts can directly inform operational decision-making or be integrated into advanced forecasting frameworks. To provide actionable guidance, this study examines the use of energy forecasts to define a guaranteed level of energy production. The minimum energy production value, as projected by all ensemble members of the seasonal forecasting system, did not exceed the corresponding measured value in 40 out of the 42 months examined, which is equivalent to 95% of the assessment period. On average, this minimum represents 44% of the observed production. Thus, the minimum value among all ensemble members for each month can be used as a lower bound for guaranteed wind energy production. Figure 6 presents a comparison of the minimum ensemble forecast with the measured values (Ground Truth).

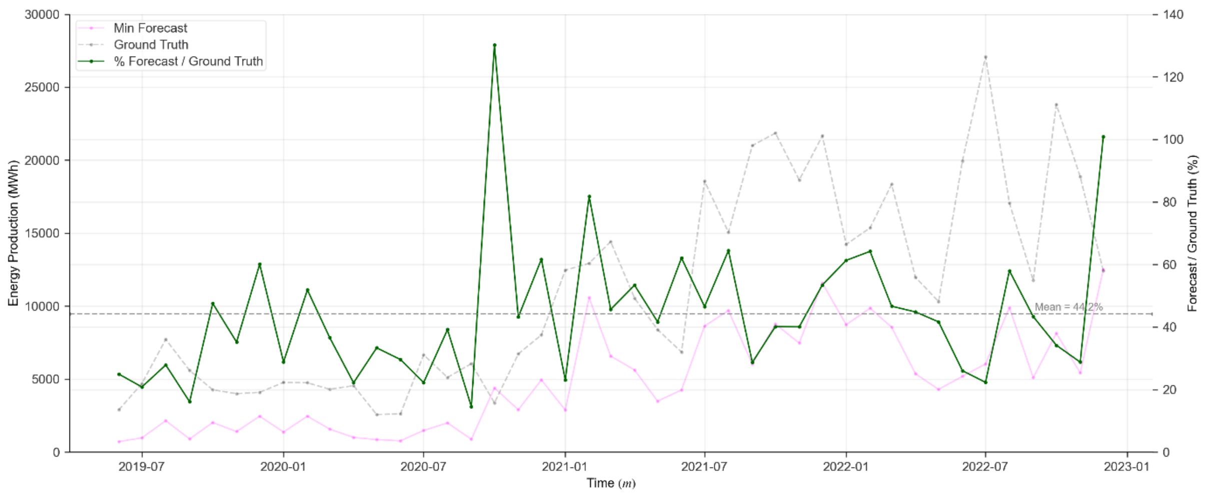

Figure 6: The comparison between the measurements at the Paradeisi substation and the minimum values of the monthly energy production forecasts from all ensemble members of the seasonal forecasting system, for the period from June 2019 to December 2022.

4.3 Composite forecasts

At the same time, energy forecasts generated by different ensemble members can be combined to produce higher-quality forecasts. Simple statistical methods or machine learning techniques are employed to select the best ensemble member or to synthesize the results from all members [1]. Since the forecast error varies significantly when calculated for each month individually, the approach adopted is to compose forecasts by selecting the single best-performing member for each month of the year. The best-performing member for each month is selected based on the minimum MAE over the entire period from June 2019 to December 2022. These selected members are listed in Table 2.

Table 2: The best-performing members.

Month	1	2	3	4	5	6	7	8	9	10	11	12
Ensemble member	23	27	13	3	19	14	34	20	37	4	40	7

Because the selection of the 12 members is based on data from all 42 months, the calculated error represents an upper bound of the forecasting skill. Using the best-performing members, a 42-month time series of energy production forecasts is constructed and compared with the corresponding measured values at the Paradeisi substation. This comparison is presented in Figure 7.

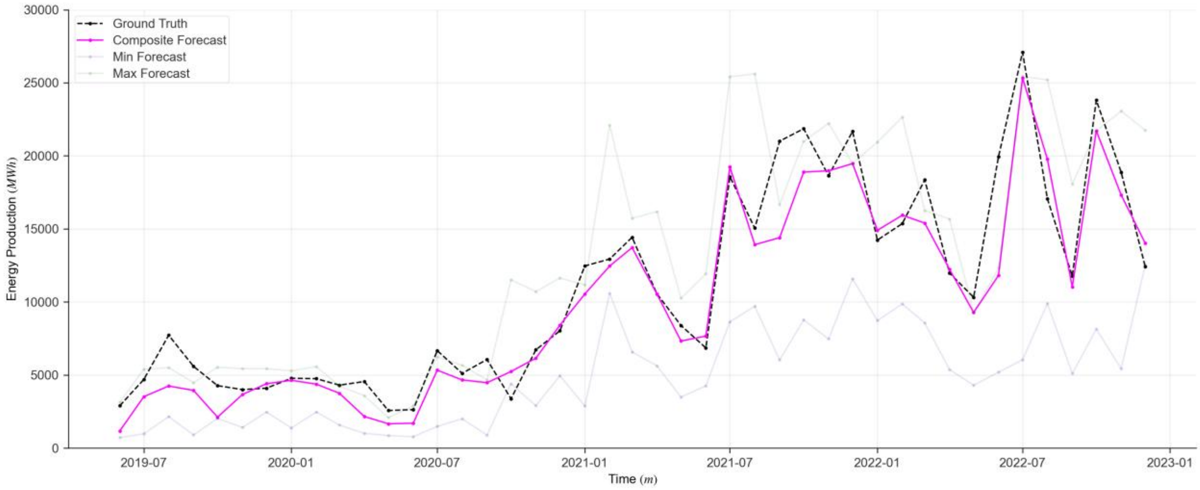

Figure 7: The measurements and composite forecasts of the energy production from the WTs connected to the Paradeisi substation for the period from June 2019 to December 2022.

The total energy measured from June 2019 to December 2022 was 476,535 MWh, while the forecasted total energy production for the same period was 431,596 MWh, representing 91% of the measured value. Forecasting skill improves when evaluated over longer time periods. Conversely, on a monthly basis, larger differences between observed and forecasted values arise, with composite forecasts often underestimating the measurements. The errors calculated using four statistical metrics are shown in Table 3. According to the MAE metric, the mean absolute error is 1,518 MWh, with a mean percentage error of 17%. Since production levels were lower before 2021 than afterward, the WAPE metric, which weights errors according to actual measurements size, is considered a more objective indicator. Based on WAPE, the mean percentage error remains below 14% of the measured production.

Table 3: The error of the composite forecasts of the energy production from WTs connected to the Paradeisi substation for the period from June 2019 to December 2022.

Metric	MAE	RMSE	MAPE	WAPE
Value	1517.66MWh	2170.98MWh	17.40%	13.69%

5.DISCUSSION

The computed forecast error aligns well with findings reported in the literature, given that: a) machine learning models generally perform better than physics-based models, especially when in-situ measurements from wind farms (WFs) are used; b) combining forecasts over larger areas and multiple WFs usually reduces errors; and c) errors tend to increase with longer forecast lead times [1], [17]. For example, one study [18] reported monthly forecasting errors using eight ML models and real data from a large WF in Ethiopia (153 MW, 102 turbines), with errors (MAPE) between 6.9% and 7.6% for the best models, and around 15% for less advanced ones. This WF is larger than those in the present study (102 vs. 61 turbines) and also applied machine learning methods. Another study [19] found errors from 12.9% to 17.2% for a large WF in China and 13.3% to 15.8% for a similar WF in the US, using three different machine learning models with on-site data.

The methodology employs the Weibull approach to estimate wind energy potential at a regional scale rather than focusing on individual turbine performance. This approach enables broader assessments, where random errors often balance out, but it also introduces uncertainty due to several simplifying assumptions. It does not account for variations in air density, and the use of the power law with a constant exponent overlooks meteorologically driven changes in the vertical wind speed profile. Additionally, the Weibull distribution may not always accurately represent the actual wind speed potential, often leading to an underestimation of energy production, while static wind power curves may not fully capture real-world factors such as yaw misalignment [20], [21]. Many of these challenges can be partially addressed by using more advanced computational methods and incorporating richer, site-specific datasets that better reflect local atmospheric and operational conditions, forming a foundation for further research, which in turn will advance the quality of predictions.

6.CONCLUSIONS

This paper presents a methodology for generating medium-term wind energy production forecasts using sub-daily wind speed forecasts from a seasonal forecasting system. Applied at the substation level within the Greek NIS, the forecasting skill was evaluated against actual measurements. The methodology is scalable and can be extended to the regional level.

The methodology comprises five key steps. First, geospatial and design data for the WFs under study are collected. Next, the locations of the WFs are matched with wind speed forecast points. Subsequently, wind speed forecasts are extrapolated to the hub height of each WT. Then, the parameters k and C of the monthly Weibull distributions are estimated. Finally, energy production is calculated based on these distributions and the design characteristics of the WTs studied.

Energy forecasts were generated from wind speed predictions at an enhanced spatial resolution of 9 km × 9 km, measured at 10 m above ground level. The raw predictions were produced by the ECMWF SEAS5 seasonal forecasting system, which comprises 51 ensemble members. Energy production is forecasted monthly with lead times spanning one to seven months from the forecast issuance date.

The methodology was applied at a substation in south Euboea connecting four WFs. Forecasting skill was assessed for all ensemble members over a 42-month period (June 2019 to December 2022). To produce actionable signals, two synthesis approaches were explored: selecting the best-performing member for each month, and using the minimum value across all ensemble members as a lower bound estimate, or guaranteed monthly energy production.

The minimum forecast values across the full ensemble did not exceed the corresponding measurements on a monthly basis in 40 of the 42 months examined. Therefore, these minimum values can serve as a conservative lower bound for WF production, averaging 44% of the measured output.

By selecting the 12 best-performing ensemble members to create a composite time series of energy production forecasts, the MAPE was 17% and the WAPE 14%, based on a 42-month sample that corresponds to seven forecast sets. These results represent an upper bound of forecasting skill, as member selection utilized the entire error dataset. This error is expected to decrease with additional forecast sets, enabling improved member selection. Extending the error dataset and optimizing the member selection is proposed for subsequent research.

Acknowledging the above and considering the exhibited forecasting performance, the development and use of seasonal forecasts for the wind energy sector constitute a realistic and feasible option. These forecasts can be effectively utilized on their own or integrated into more comprehensive forecasting frameworks.

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CLIMPACT

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REGIONAL PLANNING FOR ADAPTATION TO CLIMATE CHANGE IN GREECE: A PRELIMINARY ASSESSMENT OF IMPLEMENTED AND PLANNED ACTIONS

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ABSTRACT

Greece's National Adaptation Strategy (NAS), released in 2016, aims to increase country's resilience against climate change, by providing guidelines, followed by the elaboration of concrete measures at regional level through the development of 13 Regional Adaptation Action Plans (RAAPs). The 13 Regions of Greece have developed the initial RAAPs, seven of which have already been approved, while the process, for the other six, is ongoing. The present work focuses on mapping, assessing and prioritizing the adaptation measures suggested in all 13 RAAPs, as well as those that have been implemented or are planned to date. To this scope, this analysis first classifies the proposed climate change adaptation measures included in RAAPs into three main categories (soft, development, and hard), indicating also the respective adaptation sector and then assesses the level of implementation at critical pilot Regions via structured interviews with regional officials from the relevant departments at each pilot Region. These interviews focus on identifying the selection criteria for the adopted measures, the prioritization of future actions/measures, the available financial instruments, and the potential socio-economic impacts. The initial analysis of the first interviews revealed the differentiation of maturity level and implementation performance of measures among the Regions creating the need to develop a systematic approach/tool to monitor and assess the performance of the implemented adaptation measures. Obstacles with respect to the social acceptance of the suggested adaptation measures are also crucial to be explored.

Keywords: Regional Adaptation Plans; prioritizing climate adaptation measures; financial instruments; social acceptance; willingness to pay.

1. INTRODUCTION

In response to the European Union's encouragement to develop and implement adaptation measures across all sectors of the society and economy, Greece has drafted the first version of its National Adaptation Strategy (NAS) in 2016 [1]. NAS was formally endorsed through Law 4014/2016 [2] and has also been incorporated into the current legal framework, i.e. the National Climate Law [3]. NAS proposes indicative actions and measures to promote effective adaptation within the framework defined by the United Nations Convention on Climate Change, European policies and international experience. Greece has aligned its national framework with the European guidelines, such as the EU strategy on adaptation to climate change [2], and therefore regional adaptation planning is mandatory. Specifically, each Region of Greece is called upon to develop its Regional Adaptation Action Plan (RAAP). RAAPs specify the guidelines provided by NAS for each environmental, economic, and social sector expected to be significantly impacted by climate change. RAAPs assess climate vulnerability and determine appropriate actions and measures for adaptation to climate change based on the specific characteristics of each Region. The 13 Regions of Greece have already developed the initial RAAPs, seven of which have already been approved, while the process, for the other six, is ongoing.

The present work focuses on classifying the proposed climate change adaptation measures included in all RAAPs, in order to explore the similarities and differences in regional adaptation needs. To this scope, the proposed climate change adaptation measures are classified into three main categories (soft, development, and hard), with the adaptation sector they address also indicated. Subsequently, in order to assess the progress of the Regions' adaptation, interviews are conducted with executives from the relevant departments at critical Regions. These interviews focus on identifying the selection criteria for the measures adopted, the prioritization of future projects, the available financial instruments, and the potential socio-economic impacts.

2. METHODOLOGICAL APPROACHES

2.1 Classification of proposed adaptation measures

The climate change adaptation measures indicated in the 13 Greek RAAPs could be classified into the following main categories:

- Soft measures: Measures that aim to change human behavior and forms of governance. Examples of soft measures include informing and raising awareness among citizens, strengthening and promoting social dialogue, and establishing Climate Change Departments in the Region.

- Development measures: Actions/studies that lead to the development of knowledge about climate change, its impacts, and the effectiveness of adaptation measures. Examples include the development of monitoring systems, vulnerability studies and management plans.

- Hard measures: Measures mainly related to infrastructure development or transformation (e.g., energy upgrading of public buildings), changes in the functions of various economic activities (e.g., changes in farming/livestock practices), or even the relocation of certain activities to new locations (e.g. the relocation of existing activities from coastal areas at increased risk).

Moreover, each suggested measure can be defined by the adaptation sector it relates to. NAS includes adaptation measures related to the following 15 environmental/societal/economic sectors: *agriculture & livestock farming, forestry, biodiversity & ecosystems, fisheries, aquaculture, water resources, coastal zones, tourism, energy, infrastructure & transport, health, built environment, mining industry, cultural heritage, and insurance sector*. In general, RAAPs do not align strictly with the NAS' sectoral classification of the proposed measures. For instance, the RAAP of Eastern Macedonia and Thrace Region includes in its analysis the manufacturing sector, while the RAAP of North Aegean Region differentiates measures related to flood protection from the broader category of water resources. In the framework of the present analysis, NAS sectorial categorization has been adopted, with the difference that the fisheries and aquaculture categories have been merged. This is primarily because these categories are managed together in most plans; therefore, this consolidation facilitates the current analysis. Additionally, the present analysis includes a broader category, namely 'horizontal/cross-sectoral measures', which includes horizontal measures (e.g. the development of a climate change observatory) as well as cross-sectoral measures (e.g. the development of an integrated early warning system for risks related to agriculture, livestock farming, forestry, and the built environment).

2.2 Interview process

To assess the level of implementation of the proposed measures included in RAAPs, structured interviews have been conducted with regional officials from the relevant departments in critical pilot Regions. In the context of this study, the Regions considered critical are those identified as the most vulnerable in the NAS's vulnerability study. NAS's vulnerability study is based on total economic damage per Region and considers the economic activities that take place in each Region. According to the NAS analysis, regions can be classified into three levels of vulnerability: low, medium and high. At the time of writing, interviews had been conducted with regional officials from two Regions: one highly vulnerable (Region of Crete) and one moderately vulnerable (Ionian Islands Region). Interviewees are asked to respond regarding the status of adaptation projects implemented or planned by the Region, the type of measures involved (soft, hard or development), whether a systematic method of recording performance has been planned, and the obstacles to acceptance by the local community. If no measures have been implemented or planned to date, officials are asked to indicate the measures they would consider most important to plan in the Region based on their experience.

3.RESULTS ANALYSIS

3.1 Analysis of RAAP's adaptation measures

Categorizing measures by sector has shown that the water resources sector requires the most adaptation measures at national level (Fig. 1). Specifically, this sector requires a significant number of hard measures, such as the construction of flood protection works and the upgrading of the irrigation and water supply networks, as well as the implementation of water reuse. At the same time, further development actions are required to adapt this specific sector, such as the development/upgrading of monitoring systems (e.g. surface runoff and water quality monitoring systems) and the establishment of effective management plans (e.g. water scarcity and flood risk management plans).

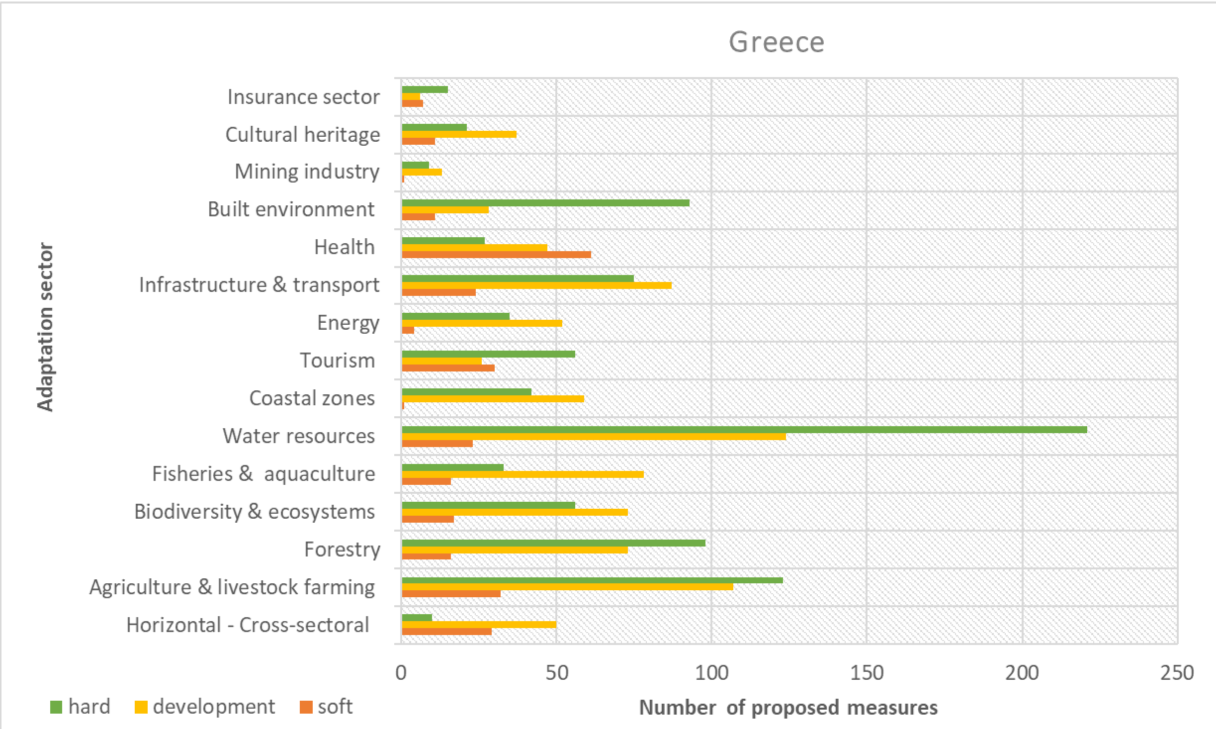

Figure 1: Classification of proposed adaptation measures included in Greece's RAAPs

Table 1 shows the sectors at each Region that require the greatest number of soft, development and hard measures to be adopted. In the case of Crete, a pilot Region for conducting interviews in the context of this study, agriculture and livestock farming requires the greatest number of *hard measures*, especially financial incentives/disincentives to promote the implementation of adaptation measures by the relevant parties. The sector requiring the most *development measures* in Crete is water resources. Accordingly, in the Ionian Islands Region, the water resources sector requires the greatest number of *hard measures*, while the infrastructure & transport sector requires the most *development measures*.

Table 1: Predominant sectors for adaptation measures per Region

Region	**Measure category**		
	soft	**development**	**hard**

Attica	Agriculture & livestock farming	Health	Agriculture & livestock farming
Central Greece	Horizontal - Cross-sectoral	Agriculture & livestock farming	Water resources
Peloponnese	Horizontal - Cross-sectoral	Water resources	Water resources
Crete	Health	Water resources	Agriculture & livestock farming
Western Macedonia	Health	Infrastructure & transport	Water resources
Central Macedonia	Health	Forestry	Water resources
Eastern Macedonia and Thrace	Horizontal - Cross-sectoral	Water resources	Forestry
Thessaly	Infrastructure & transport	Fisheries & aquaculture	Water resources
North Aegean	Horizontal - Cross-sectoral	Water resources	Water resources
South Aegean	Horizontal - Cross-sectoral	Water resources/ Biodiversity & ecosystems	Water resources
Ionian Islands	Health	Infrastructure & transport	Water resources
Epirus	Tourism	Water resources	Agriculture & livestock farming
Western Greece	Health	Agriculture & livestock farming	Coastal zones

3.2 Findings from the interviews

The interviews were carried out with members of the RAAP implementation project team to evaluate the progress of the RAAP implementation of Crete including the Environment Directorate, and the Civil Protection Directorate. The Region of Crete mainly implements measures that can be classified into soft and hard adaptation measures. Examples of hard measures include flood protection techniques, coastal erosion protection, the construction of dams and reservoirs, and the relocation or prohibition of activities. The Civil Protection Directorate plays an important role in the implementation of soft measures. In accordance with its institutional role, it is responsible for providing information and disseminating guidelines and preventive and response measures, mainly to municipalities and local authorities. A typical example is the daily update of fire risk: The Daily Fire Risk Forecast Maps produced by the Civil Protection General Secretariat are used by the regional Civil Protection authority to inform municipalities, local authorities, and citizens. The effectiveness of the Region of Crete Civil Protection Directorate efforts is reinforced by the performance of the early warning systems that have been developed.

The Region of Crete also participates in many development projects (EU funded and co-financed). A particularly important development project includes the “Regional Support Mechanism of Crete for Adaptation to Climate Change”. The project is not limited to the development of a climate change observatory; it also aims to monitor the implementation of the adaptation actions and measures included in Region of Crete’s RAAP, as well as redefining vulnerability and the necessary adaptation measures per sector. An important development project is the installation, operation, and maintenance of automatic meteorological and hydrological network, which monitors climate variability and water resources parameters in Crete. The network has been developed by the Decentralized Administration of Crete, which acts as an advisor to the Region of Crete and the municipalities as far as their water needs, the periods of drought, extreme weather and flooding conditions, so that appropriate measures should be adopted.

Regarding the social acceptance of the implemented adaptation measures, the Civil Protection Directorate of the Region of Crete reports that there have been no difficulties with the acceptance of the measures adopted so far. Conversely, the Water Directorate of the Decentralized Administration of Crete acknowledges that soft measures are rather ineffective unless accompanied by hard measures, such as economic incentives/disincentives which promote the implementation of adaptation measures. In particular, actions that are considered restrictions in the development of the tourism and agricultural sectors —which are highly dependent on the island's natural resources and therefore on climate conditions— may be met with reservation by the related parties.

The interview with the Region of the Ionian Islands official highlighted the anticipation for the approval of the Region's RAAP. RAAP's draft has been finalized, and its approval is expected to facilitate the implementation of adaptation measures. Furthermore, the interview emphasized the importance of the LIFE-IP AdaptInGR project. The project 'LIFE-IP AdaptInGR — Boosting the implementation of adaptation policy across Greece' aims to strengthen the implementation of the NAS and the 13 RAAPs [5]. As part of the project, an innovative system to monitor the vulnerability of the Ionian Islands coastal zone to the adverse impacts of climate change is developed and 50 carefully identified beaches across the Ionian Islands Region are being monitored for potential erosion problems in order to identify beaches that immediate action is needed.

4.CONCLUSIONS

The review of Greece's 13 RAAPs emphasizes the necessity not only to implement hard measures but also to constantly monitor the climate change impacts and the effectiveness of the implemented measures, especially in the water resources sector. The importance of monitoring is demonstrated by the significant number of development measures included in the RAAPs and by interviews with executives of the pilot Regions. However, social acceptance is crucial for the effective adoption of the proposed adaptation measures. Therefore, obstacles with respect to the social acceptance of the suggested adaptation measures should also be explored.

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CLIMPACT WEB DATA PORTAL: AN INNOVATIVE PLATFORM FOR CLIMATE AND ENVIRONMENTAL DATA

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ABSTRACT

CLIMPACT Web Data Portal is an innovative and dynamic platform, open and accessible to all, designed to efficiently store, visualize and manage geospatial data including climate and environmental data and data derived products, from in-situ measurements, satellite observations, and model outputs. Tailored to meet the needs of scientists and stakeholders, the platform facilitates seamless access to high-quality and valuable climate data and information, providing at the same time fast browsing and selection of the available data through a dynamic web map. The platform aggregates and harmonizes data from more than ten organizations from the public and private sectors working on the evaluation of the impacts of climate change and adaptation measures, creating a unified and comprehensive resource for research and decision-making. By leveraging modern technologies, open-source tools, and standardized nomenclature, it promotes transparency, interoperability, and long-term sustainability. The platform aligns with the FAIR (Findable, Accessible, Interoperable, Reusable) data principles and the broader vision of Open Science, ensuring that climate-related information is accessible, trustworthy, and ready to support evidence-based decision- making and research.

Keywords: Climate change, web portal, geospatial data, data management, open source, PaaS, data visualization, repository

1. INTRODUCTION

Climate change constitutes one of the most critical and complex challenges contemporary societies are called to confront, with profound implications at the local, regional, and global levels. In Greece, rising temperatures, prolonged heatwaves, recurrent wildfires, and increasing water scarcity have already begun to threaten ecological stability, human health, and key economic sectors such as agriculture and tourism [1]. At the European level, the challenge is differentiated yet interlinked: southern regions face acute water scarcity and wildfire risk, whereas northern regions are increasingly exposed to flooding and sea-level rise [2], [3]. These climatic pressures are testing the European Union's strategies for energy transition, socioeconomic cohesion, and climate adaptation, thereby testing both societal resilience and policy integration. Globally, the accelerating rise in greenhouse gas concentrations continues to drive systemic risks, including disruptions to food and water security, biodiversity loss, forced migration, and heightened geopolitical instability [4]. Climate change is therefore a complex problem that requires coordinated, science-based, and long-term actions at multiple levels.

To tackle these challenges, the Hellenic Scientific community has joined efforts under the "National Research Network for Climate Change and its Impacts – CLIMPACT" [5], a flagship national initiative of the General Secretariat for Research and Innovation aiming to gather, synthesize, and further develop the relevant national scientific and research multidisciplinary and cross-sectoral activities in order to provide scientific expertise, innovative tools, and services for mitigating the effects of and adapting to the Climate Change.

The initiative to establish a scientific network on Climate Change started in 2017, through the collaboration of the National Observatory of Athens, initially with the Research Division of the Ministry of Education, Research and Religious Affairs, and later with the Ministry of Development and Investments. The first phase launched in 2019, and the second phase started in 2023 with funding from the Ministry of Development. The goals of the current second phase are: (a) to fully integrate the country's scientific and research institutions and coordinate their collective, targeted efforts on Climate Change issues, and (b) to establish CLIMPACT as the nation's primary scientific pillar on Climate Change in support of the State and Society through reliable, evidence-based expertise Today the CLIMPACT Network consists of 28 Research Institutes, Universities and Organizations from Greece and Cyprus, and participation is open to new members who wish to join (as affiliated member) and contribute to the study and management of the impacts of Climate Change [6].

Effectively addressing climate change requires climate and environmental data that are accurate, timely, and readily accessible, enabling informed research, policy, and decision-making. In Greece, a country highly vulnerable to climate-induced hazards such as heatwaves, wildfires, droughts, and floods, the need for an integrated approach to climate data is particularly urgent.

In this work we present the CLIMPACT Web Data Portal [7], that is being developed by the Hellenic Centre for Marine Research within the CLIMPACT phase 2 Project (2023 - 2026), an innovative and dynamic platform designed to facilitate scientists, policymakers, and stakeholders to access high- quality climate and environmental data, information and data products.

2. METHODOLOGY

The CLIMPACT Web Data Portal is built on principles of openness, accessibility, and sustainability. Designed as a modern digital infrastructure, the platform provides a centralized environment for hosting, sharing, and exploring climate and environmental datasets of national and regional importance. Its primary objective is to make data Findable, Accessible, Interoperable, and Reusable (FAIR) [8], [9], actively supporting European and National policies for Open Data and Open Science [10].

By adhering to the FAIR principles, the portal ensures that datasets are not only available but also well-documented, standardized, and compatible with international standards and best practices. This approach enhances their value, enabling researchers, policymakers, educators, and privates to use, re-use and combine data across disciplines and sectors. By reducing duplication of effort, the platform encourages efficiency, fosters collaboration, and accelerates innovation.

At the same time, the CLIMPACT Web Data Portal is designed to serve different types of users and needs. Whether supporting scientific research, policy development, or public awareness, it provides reliable access to up-to-date climate and environmental knowledge. In this way, the portal acts as a bridge between science and society, making complex information and knowledge more transparent and actionable.

3. DATA SOURCES

During the CLIMPACT phase 1 Project (2019-2022), the Athena Research Centre developed the CLIMPACT data catalogue [11], a structured data inventory designed to host datasets submitted by Project partners along with their descriptive metadata. The catalogue enables efficient indexing, searching, and retrieval of datasets and is part of the catalogue of the Hellenic data service [12]. Future plans include exploring the linkage of the newly developed CLIMPACT data portal with the Helix e-infrastructure. Such linkage will allow the CLIMPACT Project to exploit the HELIX capabilities such as process and analysis of the climatic data sets on a cloud-based environment.

Table 1: Climatic data and products in CLIMPACT web data portal for Atmosphere, Ocean and Land

Domain	Subdomain	Parameter (ECV)	Submitted Variables	Temporal coverage	Data Provider
Atmosphere	**Atmospheric Composition**	Ozone	3	1997-2022	UoC, TUC, NKUA
		CO2, CH4 and other greenhouse gases	16	2019-2024	AUTH
		Aerosols	132	2018 -2022	TUC, Demokritos, NKUA, Academy of Athens
	Surface	Temperature	16	1901-2024	NOA, UoC, NKUA
		Precipitation	5	1901-2023	NOA
		Humidity	6	1901-2023	NOA, UoC, Demokritos, NKUA
		Pressure	5	1981-2023	NOA, NKUA
		Radiation budget	7	2006-2022	UoC, NKUA
		Wind speed and direction	7	1981-2023	NOA, UoC, NKUA
Land	**Hydrosphere**	River discharge	1	1981-2010	HCMR
Ocean	**Physical**	Sea surface temperature	1	2020	UAaegean
		Sea surface salinity	1	2020	HCMR, UAegean
		Subsurface temperature	1	2021-2025	HCMR
		Subsurface salinity	1	2021-2025	HCMR
		Subsurface currents	2	2021-2025	HCMR
	Biological/ ecosystems	Marine habitats	1	1997-2018	HCMR

At present, the CLIMPACT data catalogue is populated with contributions from the following Organizations and their respective Institutions and Departments:

- Aristotle University of Thessaloniki (AUTH),
- Hellenic Centre for Marine Research (HCMR),
- National and Kapodistrian University of Athens (NKUA),
- National Centre for Scientific Research “Demokritos” (Demokritos),
- National Centre for Social Research (EKKE),
- National Observatory of Athens (NOA),
- Academy of Athens - Research Centre for Atmospheric Physics and Climatology (Academy of Athens RCAPC),

- Technical University of Crete (TUC),
- University of Crete (UoC),
- University of the Aegean (UAegean).

These Organizations have submitted with 35 datasets covering multiple thematic and disciplinary domains, spanning more than a century of observations, starting from 1901 with atmospheric measurements from the “Thissio” historical station, up to 2024 with greenhouse gases and other atmospheric composition data. The submitted data cover the Atmosphere, Ocean and Land, with variables classified according to the Essentials Climate Variables (ECVs) [13] as defined by International Organizations and Expert Groups such as World Meteorological Organization (WMO) [14], Global Climate Observing System (GCOS) [15]. Table 1 summarizes the data that are currently available in the CLIMPACT national data base and data portal: 205 submitted variables (4th column) grouped in 16 ECVs (3rd column) for Atmosphere, Land and Ocean domains (1st column) and their components (2nd column) from more than 430 time series.

4.ARCHITECTURE AND TECHNOLOGIES

The climate data web portal employs a modern, containerized microservices architecture built on Docker to ensure scalability, portability, and consistent deployment across environments. The backend infrastructure leverages a multi-language approach, with PHP Slim Framework serving as the primary application server for web services and API endpoints, seamlessly integrated with Keycloak's OpenID Connect and OAuth 2.0 protocols for secure API authentication, while Python handles complex data processing and data ingestion. PostgreSQL serves as the primary database system, enhanced with PostGIS extensions for sophisticated geospatial data storage and querying capabilities essential for managing location-based climate datasets, satellite imagery metadata, and geographic information systems integration. The frontend is built using Vue.js, offering a responsive and interactive user interface that enables dynamic data visualization, real-time dashboard updates, and seamless user experience for accessing both direct climate measurements (temperature, precipitation, atmospheric CO2 levels) and indirect climate-related data (biodiversity indices, river discharge), utilizing specialized libraries including MapLibre GL for advanced geospatial visualization and Vue Charts for interactive data plotting, enhanced with point reduction algorithms such as Ramer-Douglas- Peucker with varying epsilon parameters to optimize rendering performance while maintaining data accuracy for large-scale climate datasets. This technology stack is orchestrated through Docker containers, enabling efficient resource utilization, horizontal scaling for handling large climate datasets, and simplified deployment of updates across development, testing, and production environments while maintaining data integrity and system reliability for critical environmental monitoring applications (Fig. 1).

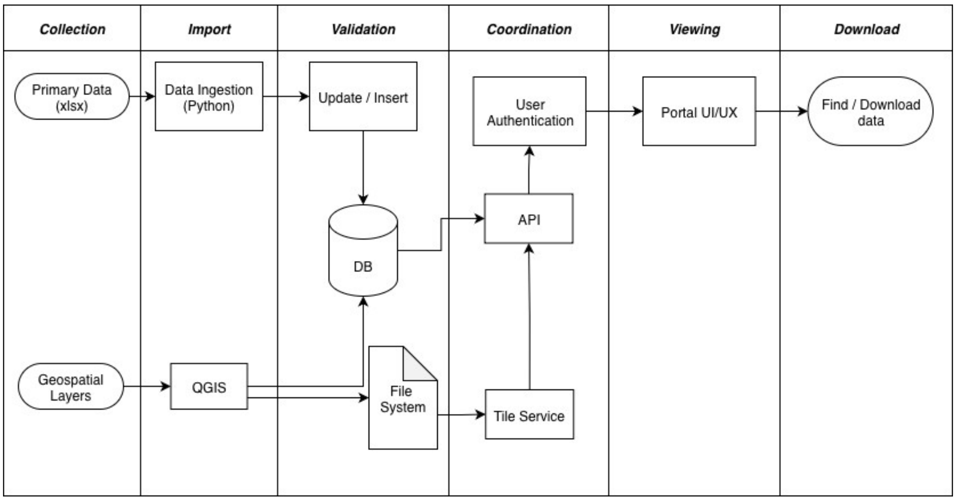


Figure 1: Climpact Web Portal System Flow Chart

The database may be considered as the core in terms of the effort applied to simplify complex relations and mitigate parts of the other systems. It was necessary to split into three main schemas according to logic grouping. These involved the metadata (fig. 2), data (fig.3) and webapp functionality (fig. 4) all interconnected to each other. The nature of primary data required to find a flexible way of storing. Since they consist of common columns that are shared between each environmental variable (depth or altitude, position, date and time) and of dynamic columns that are unique (measured parameters), the common columns were stored in a relational way and the dynamic into jsonb type entries.

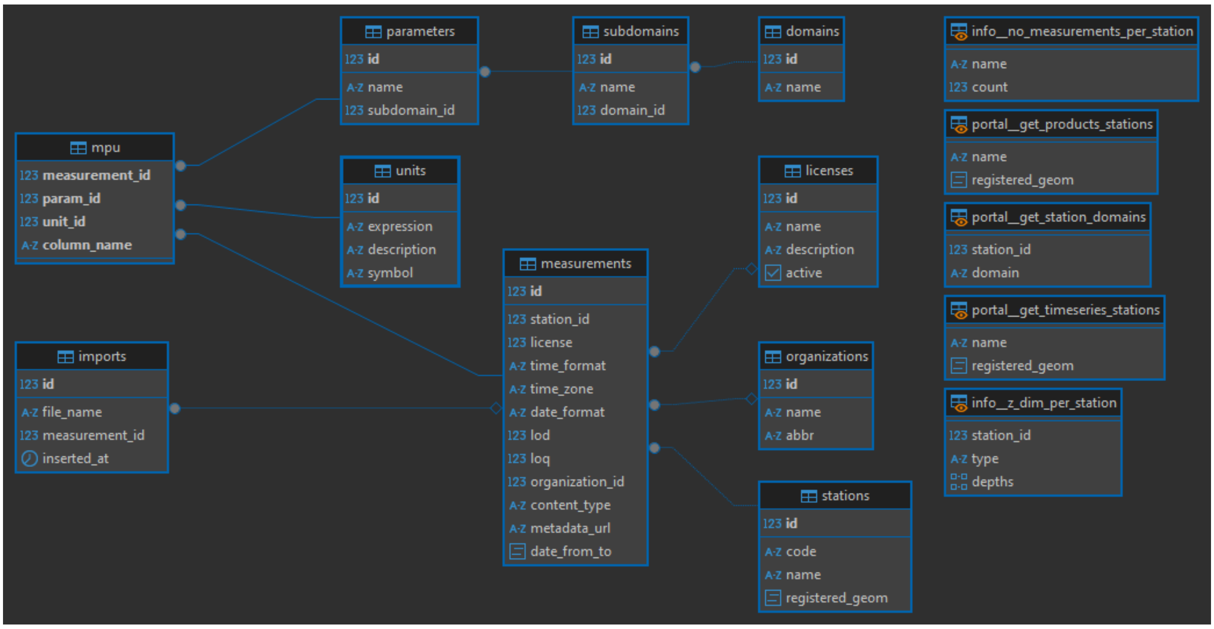


Figure 2: Metadata Schema contains information regarding the submitted data as well as dictionaries about parameters and listed variables

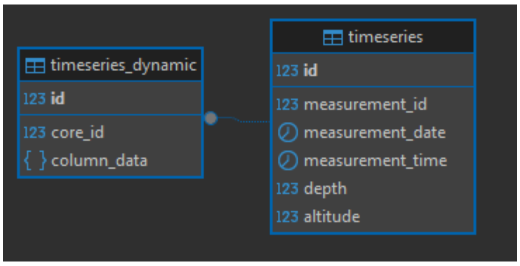


Figure 3: Data Schema contains raw data. Timeseries represent one kind of primary data. The distinction between shared and dynamic columns can be seen in the tables below

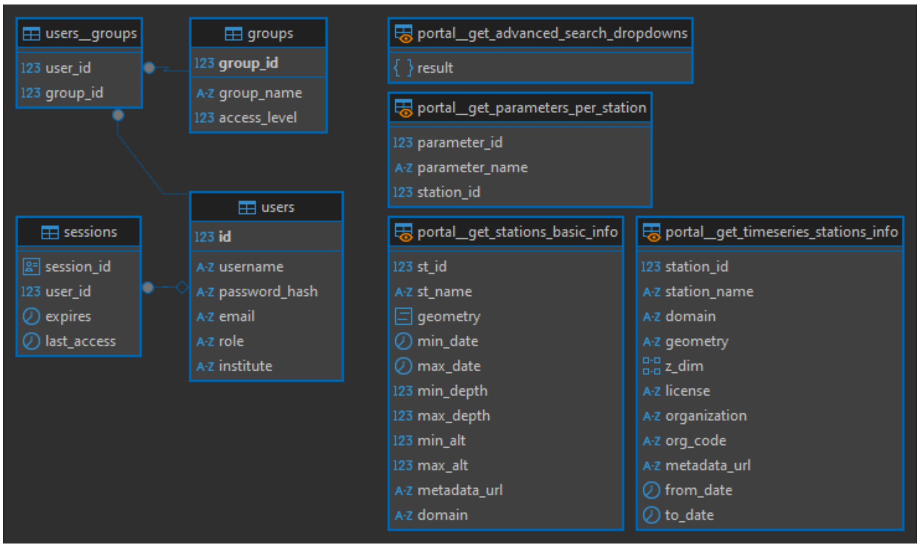


Figure 4: Webapp Schema contains configuration about the system along with mitigated programming logic in the form of views and procedures

Given the diverse range of collaborating institutes and the anticipated growth in partnerships, establishing a standardized submission template proved challenging due to varying data collection protocols, formatting preferences, and technical capabilities across organizations. To accommodate this heterogeneity while maintaining data integrity, a flexible approach was adopted utilizing simple Excel file formats with a minimum viable data pattern that preserves essential metadata and measurement standards without imposing overly restrictive formatting requirements. To ensure efficient processing of these varied submissions, a robust Python command-line interface tool was developed that can intelligently parse different Excel structures, validate data quality, perform necessary transformations, and achieve fast, reliable data ingestion while maintaining traceability and error reporting capabilities for quality assurance.

Figure 5: Python CLI tool that is used to import excel data

5.FUNCTIONALITIES AND RESULTS

The climate data portal provides comprehensive data management and visualization and download capabilities through multiple integrated interfaces. Data ingestion is handled through a Python-based command-line interface that facilitates automated import of climate datasets, while geospatial layers are seamlessly integrated using QGIS-to-PostgreSQL connections for efficient spatial data management. The web application (Fig. 6) features a dual-pane interface consisting of an interactive map section and a functional sidebar that work in coordination to provide intuitive data exploration. The sidebar houses a hierarchical layer toggling tree that allows users to dynamically control data visibility, alongside a detailed search interface (Fig. 7) with comprehensive filtering options and a dedicated search results panel for efficient data discovery. The interactive map supports full user navigation and displays clickable entities including monitoring stations, research sites (vector), and gridded data (raster), each equipped with intelligent popup windows (Fig. 8) that present preview charts for selected parameters and date ranges, as well as comprehensive metadata information about data sources, collection methods, and quality indicators. Additionally, the platform includes a data preview functionality for search results (Fig. 9), enabling users to quickly assess dataset relevance before conducting detailed analysis. This integrated approach ensures that users can efficiently navigate between spatial visualization, detailed search capabilities, and data preview functions to support both exploratory research and targeted data analysis workflows.

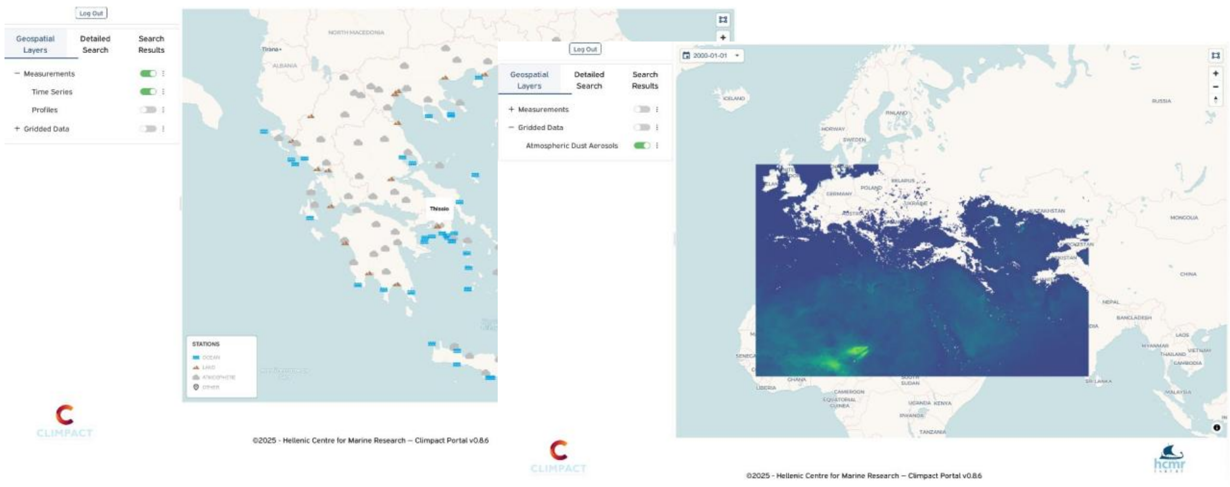


Figure 6: Main view of the portal after logging in. Examples with vector and raster layers

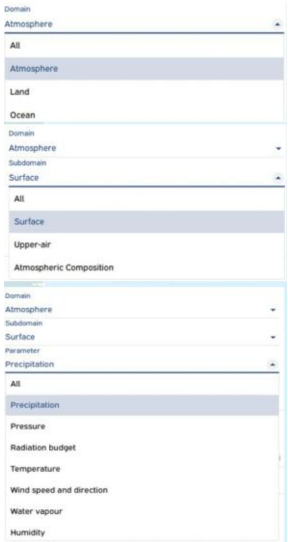


Figure 7: Detailed search components

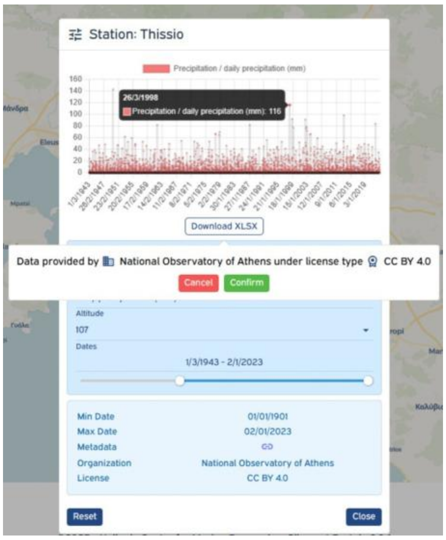
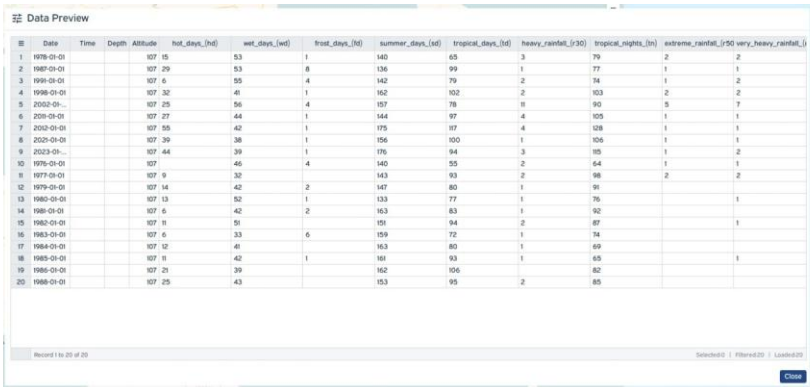


Figure 8: Entity popup with data chart, selection, download and metadata info


Data Preview

≡	Date	Time	Depth	Altitude	hot_days_(hd)	wet_days_(wd)	frost_days_(fd)	summer_days_(sd)	tropical_days_(td)	heavy_rainfall_(r30)	tropical_nights_(tn)	extreme_rainfall_(r50	very_heavy_rainfall_(
1	1978-01-01			107	15	53	1	140	65	3	79	2	2
2	1987-01-01			107	29	53	8	136	99	1	77	1	1
3	1991-01-01			107	6	55	4	142	79	2	74	1	2
4	1998-01-01			107	32	41	1	162	102	2	103	2	2
5	2002-01-...			107	25	56	4	157	78	11	90	5	7
6	2011-01-01			107	27	44	1	144	97	4	105	1	1
7	2012-01-01			107	55	42	1	175	117	4	128	1	1
8	2021-01-01			107	39	38	1	156	100	1	106	1	1
9	2023-01-...			107	44	39	1	176	94	3	115	1	2
10	1976-01-01			107		46	4	140	55	2	64	1	1
11	1977-01-01			107	9	32		143	93	2	98	2	2
12	1979-01-01			107	14	42	2	147	80	1	91		
13	1980-01-01			107	13	52	1	133	77	1	76		1
14	1981-01-01			107	6	42	2	163	83	1	92		
15	1982-01-01			107	11	51		151	94	2	87		1
16	1983-01-01			107	6	33	6	159	72	1	74		
17	1984-01-01			107	12	41		163	80	1	69		
18	1985-01-01			107	11	42	1	161	93	1	65		1
19	1986-01-01			107	21	39		162	106		82		
20	1988-01-01			107	25	43		153	95	2	85		

Record 1 to 20 of 20 Selected:0 | Filtered:20 | Loaded:20
Close

Figure 9: The user may preview a dataset after doing a detailed search

6.CONCLUSIONS

The climate data web portal could be enhanced through artificial intelligence and machine learning capabilities, enabling more advanced environmental data analysis and predictive modeling. Potential developments include machine learning algorithms that could intelligently combine diverse climate datasets—such as satellite observations, sensor readings, and socioeconomic indicators—to potentially improve climate predictions and early warning systems. An AI-assisted search engine might revolutionize data discovery by using natural language processing to interpret scientific queries and suggest relevant datasets based on research context. The platform could incorporate predictive analytics to forecast climate trends across various time scales, while machine learning models might continuously refine their accuracy through new data inputs. Future enhancements may include automated anomaly detection for identifying unusual climate patterns, computer vision algorithms for processing satellite imagery, and recommendation systems that could suggest optimal research methodologies. Additionally, the system might integrate federated learning capabilities for collaboration with other research institutions and edge computing solutions for real-time IoT sensor processing, potentially creating an intelligent ecosystem that supports accelerated climate research and evidence-based policy development.

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CLIMATE CHANGE ADAPTATION OF WATER SUPPLY SYSTEMS IN GREEK ISLANDS: THE CASE OF HERMOUPOLIS WATER SUPPLY SYSTEM

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ABSTRACT

Water supply system is one of the most significant critical infrastructures, whose resilience is directly linked to the Sustainable Development Goals of the United Nations. Water supply systems are vulnerable to the effects of climate change that include acute events, such as precipitation decrease and droughts, increased frequency of heavy precipitation events and floods, storm surges, coastal floods and erosion, extreme winds, landslides and sediment erosion, wildfires, and heat waves, as well as chronic events such as temperature increase and sea level rise.

Aiming at fostering the development of resilient, climate-proof infrastructure, including water supply systems, the European Commission (EC) released in September 2021 the Technical Guidelines on “Climate-proofing Infrastructure” for the period 2021-2027 that is divided into two pillars that are (1) mitigation and (2) adaptation, and for each pillar it is applied in two phases that are (1) screening and (2) detailed analysis. The methodology for the adaptation of infrastructure to climate change is virtually a Climate Risk and Vulnerability Assessment (CRVA).

In the frame of the emblematic national project CLIMPACT a 5-step CRVA methodology was developed for water infrastructure that is based on a literature survey and the EC guidelines. The five steps of the methodology of CLIMPACT can be adjusted for application in water supply systems as follows: (1) Description of the water supply system (1.1 determination of the main components of the water supply system and their time scale, 1.2 identification of the climate hazards for the individual components of the water supply system, and 1.3 selection of the climate indicators for each component and each climate hazard. (2) Climate change assessment (2.1 selection of the climate change scenarios, 2.2 determination of the values of climate indicators for all scenarios. (3) Vulnerability assessment (3.1 exposure analysis, 3.2 sensitivity analysis, 3.3 adaptive capacity analysis and 3.4 vulnerability analysis). (4) Risk assessment (4.1 likelihood analysis, 4.2 impact analysis, and 4.3 risk analysis). (5) Assessment of adaptation measures (5.1 identification of adaptation measures, 5.2 evaluation and selection of adaptation measures, and 5.3 integration of the selected measures into the design and the operation of the water supply system to improve its climate resilience). In the present work this methodology is briefly presented as it is currently being applied in the water supply system of Hermoupolis in Syros.

Keywords: Climate Change Adaptation; Water Supply Systems; Greek Islands; Climate Proofing; Climate risk and vulnerability assessment

1. INTRODUCTION

Water infrastructure is one of the most significant critical infrastructures, whose resilience is directly linked to the Sustainable Development Goals (SDGs) of the United Nations, which include the following:

- "Ensuring healthy lives and promoting well-being for all at all ages" (SDG3).
- "Ensuring availability and sustainable management of water and sanitation for all" (SDG6).
- "Building resilient infrastructure, promoting inclusive and sustainable industrialization and fostering innovation" (SDG9) [1].

Water infrastructure is vulnerable to the effects of climate change that include acute events, such as precipitation decrease and droughts, increased frequency of heavy precipitation events and river floods, storm surges, coastal floods and erosion, extreme winds, landslides and sediment erosion, wildfires, and heat waves, as well as chronic events such as temperature increase and sea level rise. Table 1 shows the general categories and types of climate hazards for water infrastructure, including Water Supply Systems, following the categorization of the Intergovernmental Panel on Climate Change (IPCC) [2] and the typology proposed by Stamou et al. [3] and Stamou [4].

Table 1: Categories and types of climate hazards for water infrastructure

Category of Hazard Based on IPCC	Symbol	Type of Hazard
Heat and Cold (HC)	HC1	Mean air temperature (increase)
	HC2	Extreme heat—Heat waves
	HC3	Cold spells and frost
Wet and Dry (WD)	WD1	Mean precipitation (decrease)
	WD2	Extreme precipitation
	WD3	Flooding (fluvial and pluvial)
	WD4	Aridity
	WD5	Drought
	WD6	Wildfires
	WD7	Soil erosion
	WD8	Landslide (incl. mudflows)
	WD9	Land subsidence
	WD10	Water temperature
Wind and Air (WA)	WA1	Mean wind speed (increase)
	WA2	Extreme winds
	WA3	Air quality (change)
Coastal (C)	C1	Relative (mean) sea level (rise)
	C2	Coastal flooding
	C3	Coastal erosion
	C4	Saline intrusion
	C5	Sea water temperature (and marine heat waves)
	C6	Sea water quality (incl. salinity and acidity)
Snow and Ice (SI)	SI1	Snow and land ice
	SI2	Avalanche

Table 1 depicts that there are five main categories of hazards: Heat and Cold (HC), Wet and Dry (WD), Wind and Air (WA), Coastal (C) and Snow and Ice (SI), which are further grouped into 24 types of hazards. Climate change effects are expected to intensify during the 21st century in the Mediterranean region that includes the Greek islands [5].

Currently, in most of the European countries, the design, construction, operation, financing principles, and regulatory standards for WSS do not account for climate change impacts, nor for the compound extremes and cascading infrastructure failure that were recently emphasised as very important. Aiming at fostering the development of resilient, climate-proof infrastructure, the European Commission (EC) released in September 2021 the Technical Guidelines on "Climate-proofing Infrastructure" for the period 2021-2027 [6]. The EC guidelines are divided into two pillars that are (1) mitigation and (2) adaptation, and for each pillar they are applied in two phases that are: (1) screening and (2) detailed analysis. The methodology for the adaptation of infrastructure to climate change is virtually a Climate Risk and Vulnerability Assessment (CRVA).

In the frame of the emblematic national project CLIMPACT (https://climpact.gr/main/) a 5-step CRVA methodology was developed for water infrastructure [7] that is based on a literature survey and the EC guidelines. This methodology that was applied indicatively in a Wastewater System [7] and a Dam & Reservoir System [5] can be adjusted for application in WSS as shown in Figure 1.

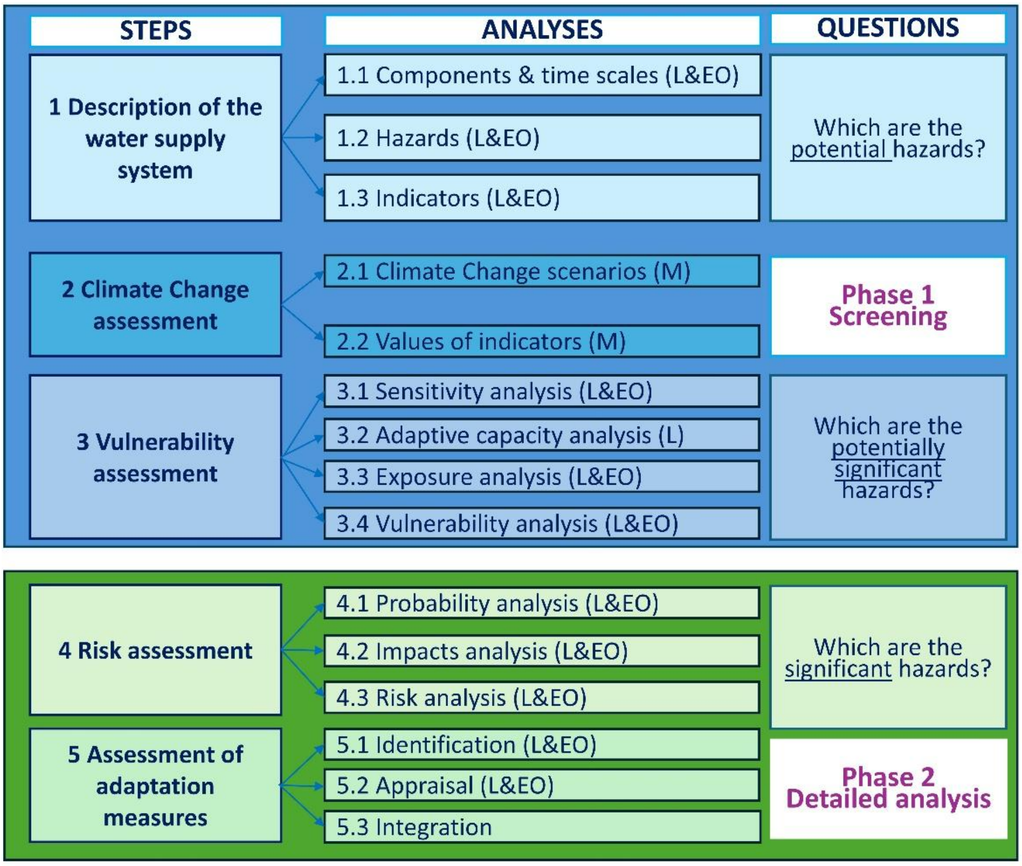

Figure 1: Climate Risk and Vulnerability Assessment (CRVA) for Water Supply Systems (L: literature survey, EO: expert opinion and M: climate models) [5,6,7]

Figure 1 depicts that the proposed methodology consists of five steps that are applied as follows:

- First phase (screening): The first 3 steps are carried out to decide whether the vulnerability of the WSS under investigation is high enough to justify proceeding to the second phase.
- Second phase (detailed analysis): Steps 4 and 5 include the risk assessment and the assessment of adaptation measures, in which targeted adaptation measures are identified, appraised and implemented to reduce the residual risks to acceptable level.

In the present work the CRVA methodology for WSS is briefly presented and how it is currently being applied in the WWS of Ermoupoli WSS (EWSS) in the island of Syros that provides drinking water to approximately 20714 inhabitants. A more detailed description can be found in [8].

2. BRIEF DESCRIPTION OF THE METHODOLOGY FOR ITS APPLICATION IN THE HERMOUPOLIS WATER SUPPLY SYSTEM

2.1 Step 1 Description of the Water Supply System

The description of the WSS consists of the following substeps:

1.1 Determination of the main components of the WSS and their time scale.

1.2 Identification of the climate hazards for the individual components of the WSS.

1.3 Selection of the climate indicators for each WSS component (determined in substep 1.1) and each climate hazard (identified in substep 1.2).

The description of the WSS requires the knowledge of (i) the characteristics of the WSS and its components and (ii) the potential impacts of all potential climate hazards on every component of the WSS; this knowledge can be primarily obtained by combining (i) a literature survey, and (ii) the opinion of experts, such as experienced engineers specialized in the design, construction and operation of WSS.

The main components of the HWSS can be categorized into five groups as follows [5,7]:

- Input of the WSS, i.e. the water source. The drinking water of the EWSS is primarily produced through desalination; thus, the input of the WSS is seawater.
- Infrastructure of the WSS. The infrastructure of the HWSS consists of the following components: (i) the desalination plant (eleven desalination units that produce drinking water, nominal production 6.800 m^3/day) and its buildings, (ii) four storage tanks (2 in Mparoumi, 1 in Anastasi and 1 in Dili), (iii) water piping from the desalination plant to the 4 tanks, and the (iv) water distribution network that consist of mainly polyethylene pipes of a total length of approximately 75 km within the city. The network comprises a total of 9.760 service connections; 7.956 of these connections are equipped with active water meters.
- Processes & hydraulics of the WSS, which in the case of HWSS include: (i) pumping of seawater to the desalination plant, (ii) desalination processes, (iii) pumping of desalinated water to storage tanks, (iv) gravity flow in the water distribution network.
- Output of the WSS that are: (i) the water for drinking water consumption and (ii) the by-products of the processes that is the brine of the desalination process including its disposal back to seawater.
- Supporting infrastructure that consist of the power supply, communications and control, transportation, access and personnel of the HWSS.

The time scale of a WSS is usually assumed to be equal to its Design Working Life that is usually about 100 years; however, it can be different for its various components. The time scale determines the scenarios of climate change that will be considered in substep 2.1.

The potential impacts that are most examined for WSS in islands can be categorized into the following five groups of climate hazards; see [9]:

- Mean air temperature increase (HC1) and extreme heat - heat waves (HC2).
- Mean precipitation decrease (WD1), aridity (WD4), droughts (WD5) and wildfires (WD6).
- Extreme precipitation (WD2) and flooding (WD3).
- Mean sea level rise (C1), coastal flooding (C2), erosion (C3) and saline intrusion (C4).
- Extreme winds (WA2).

In the literature various indicators have been proposed in water infrastructure, including indicatively the following: annual mean daily minimum temperature, annual mean daily maximum temperature, hot days, tropical nights, annual total precipitation on wet days, Consecutive Dry Days, annual count of days when precipitation is ≥ 20 mm, relative and extreme sea level rise and extreme wind speed [10]. In the case of HWSS, 1-2 indicators will be selected for each of the above-mentioned five groups of climate hazards.

2.2 Step 2 Climate Change Assessment

The assessment of climate change is performed in 2 substeps (see Figure 1):

2.1 Selection of the climate change scenarios.

2.2 Determination of the values of climate indicators (selected in substep 1.3) for all selected climate change scenarios (in substep 2.1).

Typically, climate change scenarios are selected for both historical baseline analysis and future conditions; historical analysis utilizes observed data, while future conditions are projected using climate models. In the context of the CLIMPACT2 framework, the CMIP6 and EURO-CORDEX climate models are usually employed; these models cover the period 1971-2100, incorporating SSP2-4.5 and SSP5-8.5 emission scenarios for CMIP6, and RCPs 4.5 and 8.5 for EURO-CORDEX. Due to the relatively low resolution of the climate models, their outputs can be adjusted against high resolution reanalysis datasets ERA5-Landreanalysis.

The above-mentioned scenarios will be selected for EWSS, and the values of the indicators (selected in substep 1.3) will be determined for all scenarios.

2.3 Step 3 Vulnerability Assessment

The vulnerability assessment aims at deciding whether the vulnerability of the WSS is high enough to justify proceeding to the fourth step of the methodology; it is consistent with the proposed EC procedure [6] and consists of the following four analyses (see Figure 1):

3.1 Exposure analysis.

3.2 Sensitivity analysis.

3.3 Adaptive capacity analysis.

3.4 Vulnerability analysis.

In the exposure analysis, the hazards that are relevant to the location of the WSS are identified, irrespective of its type, while in the sensitivity analysis, the hazards relevant to the characteristics of the WSS are identified, irrespective of its geographic location. The vulnerability analysis integrates the results from the exposure and sensitivity analyses to identify the potentially significant climate hazards for the WSS.

In the vulnerability assessment of the EWSS, the exposure and sensitivity analysis will be performed separately, while the adaptive capacity analysis will be incorporated in the sensitivity analysis. For consistency reasons, the same scores will be used in all three analyses, i.e., exposure, sensitivity, and vulnerability using the scale “low”, “medium” and “high”. It is expected that 4-5 of the five groups of climate hazards are expected to be potentially significant.

2.4 Step 4 Risk Assessment

The risk assessment of the WSS system to climate change consists of the following three analyses (see Figure 1):

4.1 Likelihood analysis.

4.2 Impact analysis.

4.3 Risk analysis.

The likelihood analysis looks at how likely the identified climate hazards are expected to occur within the lifespan of the WSS (determined in substep 1.1), while the impacts analysis looks at the consequences for every potentially significant hazard identified in step 3. In the risk analysis, the results of the likelihood and impact analyses are combined to formulate the risk matrix that summarizes the results of the risk analysis for the WSS and shows which are the significant climate hazards for the WSS, for which adaptation measures should be applied to reduce the residual risks to acceptable level.

The main risks of WSS in the Aegean Islands are (1) decreased water availability, (2) increased water demand, (3) degraded water quality, and (4) increased water losses; these risks are due to both climate change impacts and direct human induced factors, including intensified tourism, inefficient irrigation practices, ageing infrastructure and inadequate water management [9]. Based on the literature, in the case of HWSS, the group of hazards “mean precipitation decrease (WD1), aridity (WD4), and droughts (WD5)” will be the most significant, while some other groups can also be significant.

2.5 Step 5 Assessment of Adaptation Measures

For each of the significant hazards identified in the previous step, targeted adaptation measures will be examined and assessed following the procedure described in [6] that involves the following sub-steps:

5.1 Identification of the adaptation measures.

5.2 Evaluation and selection of the adaptation measures.

5.3 Integration of the selected measures into the design and the operation of the WSS to improve its climate resilience.

The adaptation measures can be grouped into the following five categories:

- ❖ Physical and technological measures.
- ❖ Nature based solutions and ecosystem-based approaches.
- ❖ Knowledge and behavioural change approaches.
- ❖ Governance and institutional measures.
- ❖ Economic and finance measures.

Indicative general measures for the group of hazards “mean precipitation decrease (WD1), aridity (WD4), and droughts (WD5)” in the Aegean Islands are described briefly in [9]; these include the design of infrastructure considering climate change, the development of a water loss control program, more efficient irrigation practices including smart irrigation, the application of desalination systems using renewable energy sources, rainwater harvesting and wastewater reuse systems, the implementation of emergency water plans for droughts (e.g. via mobile desalination units), and the implementation of Public-Private Partnerships mainly for the development of dams, wastewater reuse and desalination projects [9].

3. CONCLUSIONS

In the frame of the emblematic national project CLIMPACT a 5-step CRVA methodology was developed for water infrastructure that is based on a literature survey and the EC guidelines. The five steps of the methodology of CLIMPACT was adjusted for application in water supply systems as follows: (1) Description of the water supply system (1.1 determination of the main components of the water supply system and their time scale, 1.2 identification of the climate hazards for the individual components of the water supply system, and 1.3 selection of the climate indicators for each component and each climate hazard. (2) Climate change assessment (2.1 selection of the climate change scenarios, 2.2 determination of the values of climate indicators for all scenarios. (3) Vulnerability assessment (3.1 exposure analysis, 3.2 sensitivity analysis, 3.3 adaptive capacity analysis and 3.4 vulnerability analysis). (4) Risk assessment (4.1 likelihood analysis, 4.2 impact analysis, and 4.3 risk analysis). (5) Assessment of adaptation measures (5.1 identification of adaptation measures, 5.2 evaluation and selection of adaptation measures, and 5.3 integration of the selected measures into the design and the operation of the water supply system to improve its climate resilience). In this work this methodology was briefly presented as it is currently being applied in the water supply system of Hermoupolis in Syros.

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