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Integrating the Water–Energy–Food–Tourism (WEFT) Nexus into Climate Risk Assessment of Desalination-Dependent Island Water Systems: A Mediterranean Case Study

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Abstract

Mediterranean islands face increasing climate risks from rising temperatures, prolonged droughts, extreme precipitation, and sea-level rise, while seasonal tourism intensifies water and energy demand during the most vulnerable periods of the year. This study examines whether incorporating tourism as an intrinsic component of the Water–Energy–Food nexus changes the assessment of climate risks in desalination-dependent island water systems. To address this question, the Water–Energy–Food (WEF) nexus is extended to Water–Energy–Food–Tourism (WEFT) and integrated into an EU-aligned Climate Risk and Vulnerability Assessment framework. The approach is applied to the Hermoupolis Water Supply System on Syros Island, Greece, where potable water supply depends largely on energy-intensive desalination. A technically bounded climate risk assessment is compared with a WEFT-adjusted assessment that accounts for tourism-driven demand amplification and water–energy interdependencies while keeping hazard exposure and likelihood climate-driven. The results show that heatwaves constitute the dominant near-term risk because they coincide with peak water demand and high electricity requirements for desalination. When tourism amplification is included, drought-related risks shift from medium to high already in the near future for key production and pumping components, indicating earlier emergence of critical risk conditions without changes in hazard probability. Coastal risks become more important toward the end of the century, especially under high-emission scenarios. The main contribution of the study is to show that tourism-driven amplification can be operationally incorporated into sensitivity and impact assessment while preserving comparability with a conventional CRVA. The proposed WEFT–KTM framework provides a transferable basis for assessing and prioritizing adaptation in desalination-dependent, tourism-driven Mediterranean island systems.



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Keywords: WEFT nexus; climate change; Mediterranean islands; Greek islands; tourism; water supply; desalination; climate-resilient infrastructure

1. Introduction

Mediterranean islands represent some of the most climate-vulnerable socio-ecological systems, as they are increasingly affected by rising temperatures, prolonged droughts, sea-level rise, and other compound climatic pressures. According to recent literature [1,2], eight climate hazards are most frequently examined in water systems and ecosystems, out of a broader set of 24 typologized hazards [3,4]. In island environments, four additional coastal hazards must be considered, resulting in a total of twelve hazards that can be typologized into five groups: (i) mean air temperature increase (HC1) and extreme heat–heat waves (HC2); (ii) mean precipitation decrease (WD1), aridity (WD4), droughts (WD5) and wildfires (WD6); (iii) extreme precipitation (WD2) and flooding (WD3); and (iv) mean sea level rise (C1), coastal flooding (C2), erosion (C3) and saline intrusion (C4), and extreme winds (WA2).

The projected climate change impacts in the Mediterranean Region can be summarized as follows [2]: (i) HC1 and HC2: Mean air temperature and extremes will continue to increase above the global average, with heat waves intensifying in duration and peak temperature. (ii) WD1, WD4, WD5 and WD6: Mean precipitation will decrease by 4–22%, and droughts will become more frequent, severe and rapid, posing new challenges for sustainable water and agricultural management across Greece [5,6]. Furthermore, aridity will intensify, and large wildfires will increase. (iii) WD2 and WD3: Heavy precipitation and rainfall extremes will likely increase in the northern Mediterranean, potentially accompanied by more frequent flash floods. (iv) C1 to C4: Sea-level rise will enhance the risk of coastal flooding, erosion and saline intrusion. (v) WA2: Extreme wind intensity will increase.

These hazards affect water ecosystems and critical water infrastructure, particularly water supply systems, but also stormwater and wastewater networks, which are essential for public health, economic activity and social stability. In the Aegean Islands, climate change impacts are compounded by structural constraints, including limited freshwater availability, strong dependence on groundwater and desalination, ageing infrastructure and geographical isolation, as also highlighted in previous studies on small Greek islands under changing climatic conditions [7,8]. At the same time, tourism dominates the regional economy, substantially increasing population and resource demand during summer months, when water availability is lowest and energy demand peaks [9], as widely documented in Mediterranean tourism systems [10]. Recent research on the Aegean Islands has identified four dominant risks for water supply systems: (i) decreased water availability, (ii) increased water demand, (iii) degraded water quality, and (iv) increased water losses, driven by both climate change and human-induced pressures, such as tourism intensification and inefficient management practices [4]. Although tourism is recognized as a major driver, it is generally treated as external pressure rather than as an intrinsic system component. This reflects a broader Mediterranean context in which climate change increasingly generates interconnected pressures across water, energy, food, ecosystems, and socio-economic systems [11].

Despite increasing recognition of climate risks in Mediterranean island systems, most existing assessments remain sector-specific and focus primarily on infrastructure exposure and technical sensitivity [12,13]. While structured Climate Risk and Vulnerability Assessment (CRVA) methodologies provide a consistent framework for evaluating exposure, sensitivity, and risk progression, they typically treat socio-economic drivers, such as tourism, as external pressures rather than intrinsic components of the water system. In parallel, nexus-

based approaches have gained prominence as tools for analyzing interdependencies among water, energy, and food systems [14–18], while recent Mediterranean-scale assessments show that climate impacts cascade across sectors and that siloed responses may increase the risk of maladaptation [19]. In desalination-dependent islands, the water–energy coupling is particularly strong, as potable water production relies directly on electricity availability and grid stability, while in tourism-driven island economies seasonal population surges coincide with peak heatwave and drought conditions, intensifying both water and energy demand during periods of climatic stress [20,21]. This seasonality is especially important in island settings, where tourism demand peaks can create disproportionate environmental and resource pressures [22]. Recent work has also begun to examine tourism-adjusted water demand and desalination-linked system pressures in island settings [23], while renewable energy integration in seawater desalination has been further assessed as part of sustainable water-supply planning [24]. However, relatively limited attention has been given to the operational integration of nexus interdependencies into infrastructure-oriented climate risk assessment frameworks, especially for desalination-dependent island systems. Although recent studies in the Aegean region identify tourism as a major driver of increased water demand [4], its role in amplifying climate-related vulnerability and risk in infrastructure-oriented assessments remains insufficiently examined. As a result, potential amplification of vulnerability and risk during peak tourist season may be underestimated. More specifically, the extent to which tourism-driven demand amplification modifies vulnerability classification, risk magnitude, and adaptation prioritization within established CRVA frameworks remains insufficiently explored.

Against this background, the present study addresses the following research questions: (i) Can tourism be operationally incorporated as an intrinsic component of climate risk assessment for desalination-dependent island water systems? (ii) Does such integration materially alter vulnerability classification, risk magnitude, and the timing of high-risk emergence? (iii) Can the resulting risk patterns support a more policy-relevant prioritization of adaptation measures?

To address this gap, the present study extends the Water–Energy–Food (WEF) nexus to Water–Energy–Food–Tourism (WEFT) by explicitly incorporating tourism as a structural demand driver within an EC-aligned CRVA framework. The methodological novelty does not lie in proposing a new CRVA methodology, but in operationally embedding tourism-driven demand amplification within an established climate risk and vulnerability workflow. By maintaining identical hazard classifications, scoring scales, and computational structure, the analysis enables direct comparison between a technically bounded assessment and a WEFT-adjusted assessment. In particular, hazard exposure and likelihood remain climate-driven, while tourism- and nexus-related amplification effects are incorporated at the sensitivity and impact levels. This preserves methodological comparability and allows differences between the two assessments to be attributed directly to cross-sector interactions rather than to changes in the underlying CRVA structure [25]. The present analysis is designed as a baseline assessment of the current system configuration and prevailing seasonal demand structure, so as to identify how climate and tourism-related pressures may alter vulnerability and risk before the implementation of additional adaptation measures. Accordingly, the aim of the present study is to examine whether tourism-driven demand amplification and water–energy interdependencies materially alter vulnerability classification, risk magnitude, and adaptation prioritization in desalination-dependent Mediterranean island water supply systems. In addition, the study seeks to demonstrate that these interactions can be incorporated into an established CRVA framework without altering its internal logic or reducing comparability between the technically bounded and WEFT-adjusted assessments.

The remainder of the paper is organized as follows. Section 2 presents the methodological framework, including the CRVA approach and its operational integration with the WEFT nexus. Section 3 applies the proposed framework to the Hermoupolis Water Supply System on Syros Island and presents the climate change, vulnerability, risk, and adaptation assessments. Section 4 discusses the main findings and their broader implications for desalination-dependent Mediterranean island systems. Section 5 concludes the paper by summarizing the main findings and highlighting directions for adaptation planning and future work.

2. Materials and Methods

2.1. Climate Risk and Vulnerability Assessment Framework

The present study follows the CRVA methodology proposed by the European Commission [12,13]. The framework structures the analysis into five sequential steps: (1) system characterization, (2) climate change assessment, (3) vulnerability assessment, (4) risk assessment, and (5) adaptation planning.

Vulnerability (V) is defined as:

$$V = E \times S \quad (1)$$

where exposure (E) reflects the magnitude and frequency of climate hazards under specific scenarios, and sensitivity (S) represents the propensity of system components to be affected, including adaptive capacity. For hazards identified as significant, risk (R) is subsequently assessed as:

$$R = P \times I \quad (2)$$

where P denotes hazard likelihood and I represents impact severity. This structure ensures transparency and consistency in progression from screening to detailed risk analysis.

A consistent three-level classification scale (Low–Medium–High) is applied across exposure, sensitivity, vulnerability and risk to maintain methodological coherence and comparability across hazards and system components.

2.2. WEFT Nexus in Mediterranean Island Systems

Nexus-based approaches have been increasingly adopted to capture interdependencies among resource systems, particularly within the WEF framework [14–17]. In Mediterranean islands, these interdependencies are intensified by structural constraints, including limited freshwater availability, reliance on desalination, and strong tourism seasonality. In such settings, the food dimension is expressed mainly through the dependence of food provisioning systems on water and energy inputs, including water and electricity for food storage, preparation, distribution, and related service activities, as well as the increased seasonal demand generated by tourism-related food consumption. Thus, even where potable water supply is the primary infrastructure under assessment, disruptions in water and energy services can propagate to food availability and food-service activities, especially during peak summer periods.

Desalination establishes a direct coupling between water security and electricity supply [26]. Heatwaves and peak summer demand can simultaneously stress both water production and energy systems. At the same time, tourism-driven seasonal population growth substantially increases water consumption during periods of projected drought intensification [20,21]. These coinciding pressures generate compound risk conditions that extend beyond purely technical infrastructure exposure.

The WEFT perspective used here extends the WEF nexus framework by explicitly incorporating tourism as a structural demand driver. In island economies, such as those

of the Aegean, tourism significantly shapes water demand patterns and amplifies climate-induced stress [4,8]. At the same time, tourism also intensifies food-system demand through restaurants, hotels, catering services, and associated supply chains, thereby linking seasonal population growth not only to higher water consumption but also to greater pressure on food provisioning systems that depend on reliable water and energy services.

Recognizing tourism as an intrinsic element of the water system allows examination of seasonal amplification mechanisms that may modify vulnerability classification and adaptation priorities.

Figure 1 provides a conceptual representation of the WEFT nexus in the Hermoupolis Water Supply System and highlights the main interactions among water, energy, food, and tourism under climate-driven hazards.

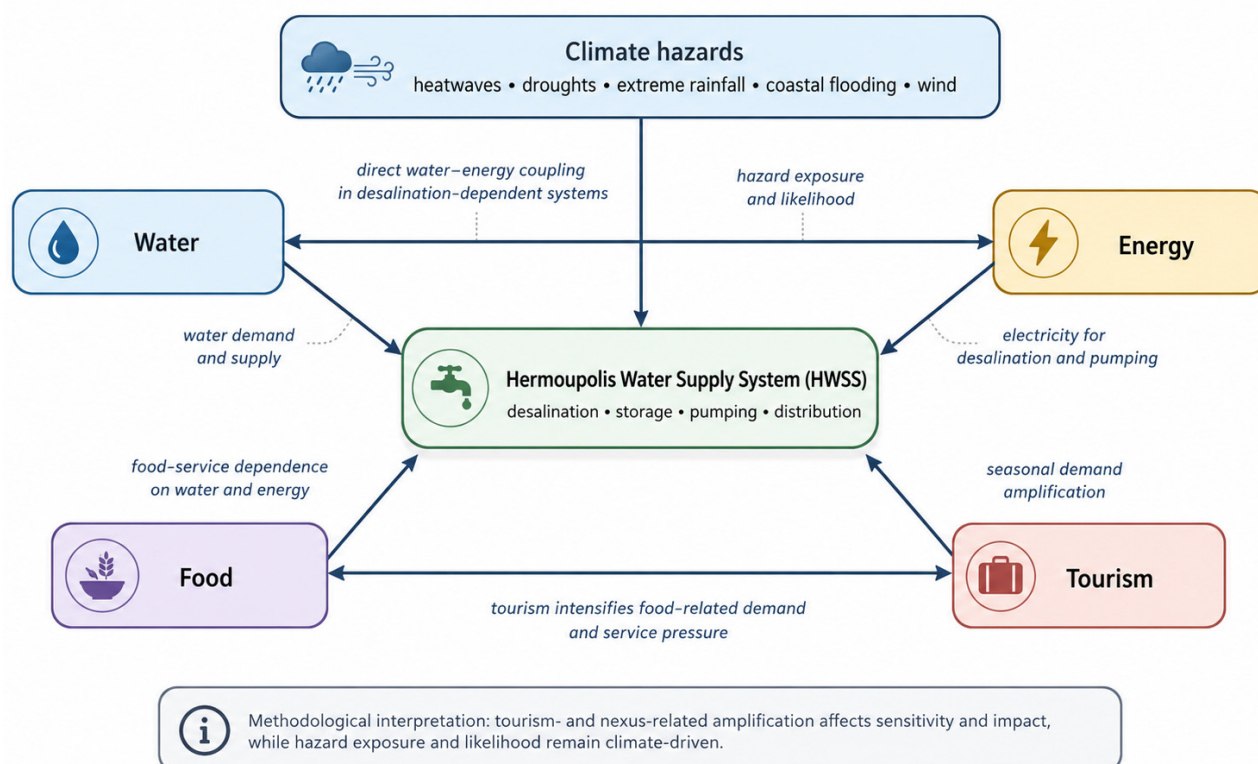


Figure 1. Conceptual representation of the WEFT nexus in the Hermoupolis Water Supply System.

2.3. Operational Integration of WEFT into the CRVA

The WEFT perspective is integrated into the CRVA framework without altering its methodological structure. Hazard identification, exposure classification, and likelihood estimation remain climate-driven and scenario-dependent, consistent with EC methodology [12]. Cross-sector interactions are incorporated at the level of sensitivity and impact, where nexus-related amplification effects may increase consequence severity. Thus, two parallel assessments are conducted: (1) a technically bounded assessment, evaluating infrastructure vulnerability within the water system boundary, and (2) a WEFT-adjusted assessment, incorporating cross-sector amplification effects while maintaining identical scales and scoring criteria. This ensures transparency and comparability while enabling evaluation of whether integrating tourism and energy coupling materially alters vulnerability, risk magnitude, and adaptation prioritization. Within this framing, adaptation measures are identified in the final step of the assessment, while their detailed comparative evaluation is left for subsequent work.

Figure 2 summarizes the methodological workflow of the CRVA–WEFT assessment and the comparison between the technically bounded and WEFT-adjusted assessments.

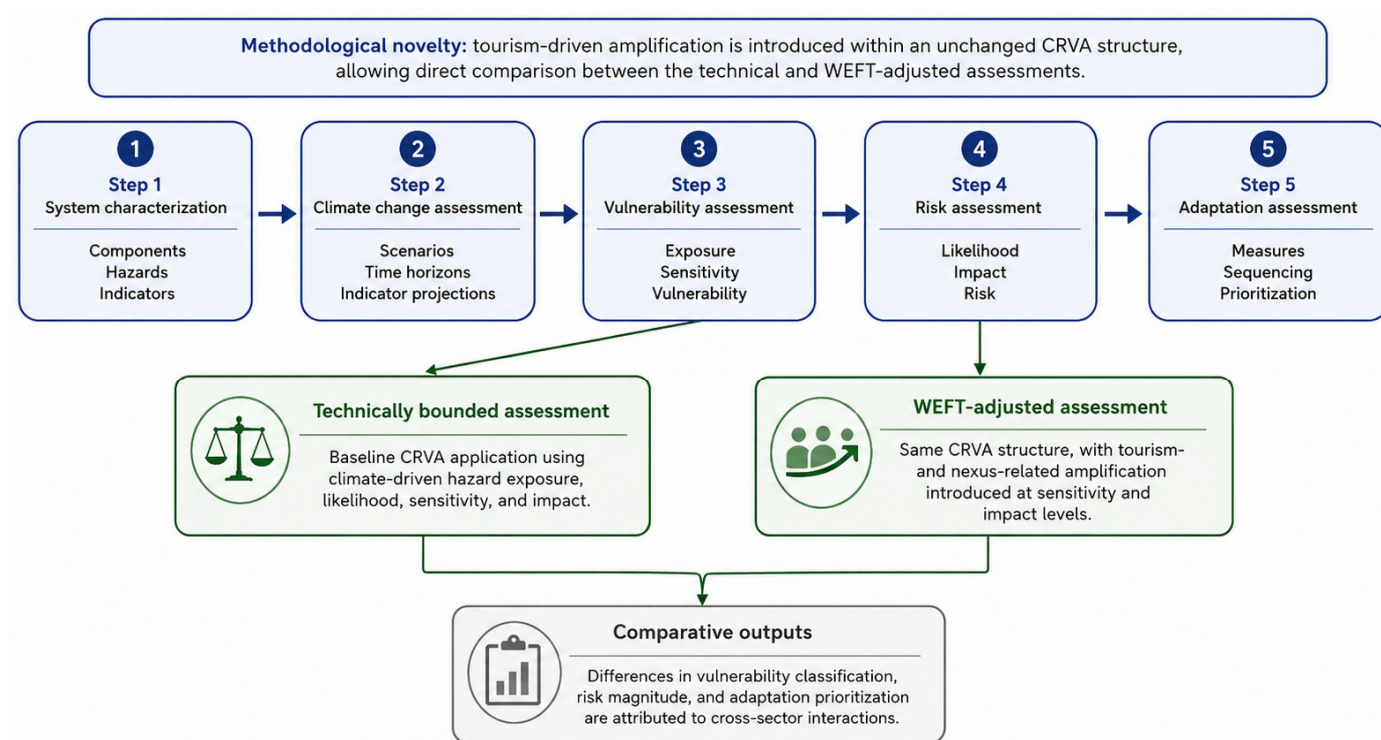


Figure 2. Methodological workflow for the CRVA–WEFT assessment and comparison between the technically bounded and WEFT-adjusted assessments.

3. Climate Risk and Vulnerability Assessment of the Hermoupolis Water Supply System

This section operationalizes the WEFT nexus within the application of a Climate Risk and Vulnerability Assessment (CRVA) methodology for water supply systems (WSS) [2], incorporating explicit WEFT extensions to account for tourism seasonality, energy coupling, and food-related service dependencies. The Hermoupolis WSS (HWSS), on the island of Syros in the Cyclades, Greece, is selected as an illustrative case for the practical application of the CRVA–WEFT assessment workflow because of: (i) seasonal tourism-related demand variability, (ii) near-total dependence on desalination, (iii) well-documented water losses, and (iv) the availability of detailed operational data for the HWSS, alongside an ongoing climate adaptation assessment [27].

Although the present case study focuses on the water supply system as the primary infrastructure boundary, the food dimension of the WEFT nexus is retained in the assessment framework through its functional dependence on water and energy availability. In Hermoupolis, food provisioning for residents and visitors depends on the continuous operation of water supply, desalination, pumping, and electricity services that support hospitality, catering, sanitation, and, where relevant, local agricultural production and commercial activities. Therefore, the food component is not assessed as a separate infrastructure subsystem, but as a dependent service domain indirectly affected by climate-driven stress on the water–energy system. In the following subsections, the five core steps of the CRVA methodology are applied.

3.1. Step 1 Description of the Hermoupolis Water Supply System

The first step involves describing the main components of the HWSS and their associated time scales, the identification of the climate hazards for these components and the selection of the climate indicators considering both the HWSS components and climate hazards.

3.1.1. Main Components of the Hermoupolis Water Supply System

The HWSS provides potable water to the Municipal Unit of Hermoupolis on Syros Island, Greece, serving the urban population (~11,000 residents as of 2021) and the seasonal influx of tourists. The water supply infrastructure has evolved in response to natural water scarcity and high seasonal demand, with desalination as its backbone, creating a pronounced energy–water nexus.

The main components of the HWSS that are typologized and categorized into five groups [3,4], which are shown in Table 1, are the following:

- Water infrastructure (A). The water infrastructure of the HWSS consists of the desalination plant (A1), the storage tanks (A2), and the distribution network (A3). The desalination plant (A1) comprises eleven reverse osmosis (RO) units with a nominal production capacity of approximately 6800 m³/d; the plant consists of eleven individual desalination units operating in parallel, with unit capacities ranging approximately from 250 to 1000 m³/day. The installation is developed on two sites, including a lower coastal area (elevation ≈ 1.5–2.0 m, area ≈ 1247 m²) and an upper area (elevation ≈ 12 m, area ≈ 4345 m²), where the main treatment units are located. The main processes include seawater abstraction, multi-stage filtration, pH adjustment, RO desalination, post-treatment, and pumping to the storage tanks. Based on operational data, the average annual production of desalinated water is approximately 1.35 × 10⁶ m³ for the period 2022–2025. The system operates continuously to meet water supply needs in the main area of Hermoupolis (≈76%) as well as in the surrounding areas, with production varying seasonally. There are four storage tanks (A2) that are located in Mparoumi (two tanks, elevation ≈81 m), Anastasi (elevation ≈111 m), and Dili (elevation ≈150 m), with a total storage capacity of approximately 3660 m³. Based on an average daily demand of approximately 3700 m³/d, the storage autonomy is estimated at approximately one day. Based on the average annual daily demand of approximately 3700 m³/d, the storage autonomy is estimated at approximately one day; during the tourist season, when demand is higher, the effective storage autonomy is correspondingly lower. This capacity corresponds roughly to one day of average demand, indicating limited buffering potential in case of supply interruptions or demand surges. The distribution network (A3) consists of polyethylene pipes with a total length of approximately 75 km. The system serves approximately 9760 connections, of which about 7956 are metered, meaning that most service connections are covered by metering. Based on the measured (i) supplied water volume to Hermoupolis of approximately 982,000 m³/year and (ii) billed consumption of approximately 577,000 m³/year for 2024, the non-revenue water (NRW) is estimated at approximately 41%. This reflects losses within the distribution system, as well as potential metering inaccuracies. This reflects non-revenue water within the system, which may include physical losses, apparent losses, authorized unbilled consumption, and operational uses, in addition to potential metering inaccuracies. The estimated NRW value is high and indicates a significant operational vulnerability of the system, although a detailed attribution of its causes would require dedicated hydraulic and operational analysis beyond the scope of the present study. Based on the permanent population served (~11,000 residents), these values correspond indicatively to approximately 245 L/cap/day on a supplied-water basis and approximately 144 L/cap/day

on a billed-consumption basis; however, these estimates include the effects of seasonal tourism demand and high non-revenue water and therefore do not represent resident-only household use.

- Processes & hydraulics (P). A seawater intake flow of approximately $14,500 \text{ m}^3/\text{d}$ is pumped (P1) from the coastal intake to the desalination plant through a pumping system and four submarine pipelines. At the plant, seawater undergoes pretreatment (filtration) prior to reverse osmosis (P2). High-pressure pumps are used to drive the RO process, incorporating energy recovery systems to improve efficiency. The produced desalinated water is then pumped (P3) to storage (P4) in four storage tanks (A2), which are located at higher elevations and supply the distribution network by gravity (P5). Water is subsequently delivered to consumption points through the network via metering (P6). The desalination plant is located at an elevation of approximately 12 m above the shoreline, requiring seawater to be pumped from the coastal intake while enabling gravity-driven discharge of brine back to the sea.
- Output (O). The output of the HWSS consists of potable water for consumption (W) and brine that is discharged to the sea (B). Water is supplied for residential, commercial, and tourism-related uses within the service area. The ratio of peak to mean water consumption is equal to 1.21, based on the comparison of average summer demand (July–August $\approx 126,000 \text{ m}^3/\text{month}$) to winter demand (January–March $\approx 104,000 \text{ m}^3/\text{month}$) for the period 2022–2025. This indicates moderate seasonal variability in water demand. The quantity of brine, including filter backwash, is estimated at approximately $8700 \text{ m}^3/\text{d}$, corresponding to a recovery ratio of approximately 40%. According to the Environmental Impact Study (EIS), the brine is conveyed through two pipelines (diameters $\Phi 315$ and $\Phi 200$) and discharged into the sea from a height of approximately 10 m. The discharge point is located in a high-wave-energy zone exposed to frequent strong northern and northeastern winds, which promote rapid mixing and dilution with seawater. Under these conditions, the elevated salinity and density of the brine are not expected to cause significant local marine impacts, as wave-induced turbulence and the elevated discharge configuration favor rapid homogenization and dispersion within a limited area around the outfall.
- Supporting infrastructure (S). HWSS's energy supply (S1) is provided via the local electricity grid, which is supplied from the mainland. The installed electrical power of the desalination plant is approximately 1.62 MW. The grid on Syros historically relied on local thermal power generation. Following its interconnection with the mainland grid, the island experienced a gradual increase in renewable energy sources within its energy mix. The operation of water production and distribution, particularly high-pressure RO desalination, is closely linked to energy availability and cost, making system operation sensitive to energy prices, supply reliability, and climate-driven demand fluctuations. Monthly energy consumption for desalination, based on operational data for the period 2022–2025, ranges approximately between 640 and 1000 MWh, with an average value of about 850 MWh/month and higher values observed during summer months. Specific energy consumption ranges approximately between 7.0 and $8.5 \text{ kWh}/\text{m}^3$. This range is consistent with the ratio of average monthly energy consumption ($\sim 850 \text{ MWh}$) to average monthly water production ($\sim 110,000 \text{ m}^3$, derived from an annual production of approximately $1.3 \times 10^6 \text{ m}^3$), yielding approximately $7.7 \text{ kWh}/\text{m}^3$. Periods of near-zero production ($\leq 1 \text{ m}^3/\text{h}$), associated with system failures, grid outages, or planned maintenance, were observed between 4 and 15 times per year during the period 2022–2025. The total duration of these events corresponds to approximately 0.1–0.6% of annual operating time, while individual events may last several hours, with maximum durations reaching up to 11 h. The operation of the HWSS (S2)

is supported by a centralized control system (SCADA), enabling real-time monitoring and control of desalination units, pumping operations, storage levels, and network performance. Communication relies on standard telemetry systems, allowing remote supervision and operational response. System functionality depends on the reliability of power supply and communication networks. Regarding transportation and access (S3), the desalination plant is located in the Ampelaki area of the Municipality of Syros, approximately 2 km from the urban center of Hermoupolis, and is accessible through the local road network. Access is generally adequate under normal conditions, supporting routine operation and maintenance activities. Although no significant disruptions have been reported, access could be temporarily affected during extreme weather events (e.g., strong winds), potentially delaying emergency response. A small team of approximately 4–6 technical staff responsible for plant operation, monitoring, and maintenance (S4) supports the operation of the desalination plant. Given the continuous operation of the desalination system, personnel availability and working conditions, particularly under extreme heat, are important for ensuring operational reliability.

Table 1. Main components of the Hermoupolis Water Supply System.

Group of Components	Main Components
Input (I)	I Seawater
Water infrastructure (A)	A1 Desalination plant including buildings, seawater piping and pumping, RO units, and potable water piping and pumping to storage. A2 Storage tanks and piping to distribution network. A3 Distribution network (piping and metering).
Processes & hydraulics (P)	P1 Pumping of seawater to the desalination plant. P2 Desalination processes. P3 Pumping of desalinated water to storage tanks. P4 Storage of potable water. P5 Gravity flow to the water distribution network and to consumers. P6 Metering.
Output (O)	W Water for consumption. B Brine disposal.
Supporting infrastructure (S)	S1 Power-electricity supply. S2 Communications & control. S3 Transportation & access. S4 Personnel.

For the purposes of the present assessment, the time scale of the HWSS is taken as approximately 100 years, representing the long-term planning horizon of the system as a whole rather than the service life of each individual component. This period is used to determine the climate change scenarios considered in Section 2.1.

3.1.2. Potential Climate Hazards and Their Main Impacts on the Components of the Hermoupolis Water Supply System

The five climate hazard groups presented in the Introduction are examined for the HWSS, namely heat hazards (HC1 and HC2), water scarcity hazards (WD1, WD4, and WD5), excess water hazards (WD2 and WD3), coastal hazards (C1 to C4), and wind hazards (WA2). For component-level assessment, these groups are represented by the corresponding hazard events: summer heatwave (EH), prolonged summer drought (ED), extreme rainfall/flash flood (ER), storm surge/coastal flooding (EC), and strong wind (EW). The hazard groups provide the typological structure, while the hazard events are used as the operational assessment units in the subsequent analysis, supporting consistent scoring of exposure and sensitivity at the component level and enabling linkage of hazards to measurable indicators and impacts. The hazard groups, hazard events, and the main component-level impacts are summarized in Table 2.

Table 2. Hazard groups and events and their main impacts on the Hermoupolis Water Supply System.

Hazard Group	Heat Hazards (HC)	Water Scarcity Hazards (WD)	Excess Water Hazards (WF)	Coastal Hazards (C)	Wind Hazards (W)
Hazard Event	Summer Heatwave (EH)	Summer Drought (ED)	Extreme Rainfall/Flash Flood (ER)	Storm Surge/Coastal Flooding (EC)	Strong Wind (EW)
I Seawater	Increased sea surface temperature (SST) → higher osmotic pressure and biofouling → increased energy demand	-	Increased turbidity and debris → degradation of intake water quality	Sea-level rise and storm surge → intake inundation and corrosion	Wave agitation → intake instability
A1 Desalination plant	Increased temperature → membrane stress and reduced efficiency → higher energy use (~7–8.5 kWh/m ³ ; up to ~1000 MWh/month in summer)	Continuous near-capacity operation (~6800 m ³ /d) → increased operational stress	Potential flooding of low-elevation units (~1.5–2.0 m) → equipment damage and production interruption (no significant events recorded to date)	Inundation and corrosion of low-lying infrastructure → electrical and mechanical failure	Structural stress and operational interruption
A2 Storage & piping to network	Increased temperature → chlorine decay and water quality degradation	Limited storage (~3660 m ³ ≈ 1 day of demand) → reduced buffering capacity	Foundation erosion → contamination risk	-	Minor structural stress
A3 Distribution network (~75 km, NRW ~41%)	Peak demand (~+21%) → pressure drops and network stress	Soil shrink–swell → leakage increase → amplification of non-revenue water (~41%)	Pipe exposure and scour → local failures	Saline intrusion and corrosion in low-lying sections	Minor indirect effects
P1 Pumping of seawater	Increased temperature → higher pump load and energy demand	Extended operation duration → increased wear	Debris clogging → reduced intake efficiency	Inundation risk → pump failure	Intake disturbance due to wave action
P2 Desalination processes	Increased temperature → reduced reverse osmosis efficiency → higher specific energy consumption	Continuous high utilisation → increased failure consequences	Feedwater quality variability → increased pretreatment demand	Increased SST → fouling and osmotic pressure → higher energy demand	-
P3 Pumping to storage tanks	Increased pumping demand → higher electricity use	Extended pumping cycles → reduced operational flexibility	Power disruption risk	Indirect effects via coastal impacts on grid	Indirect effects via grid instability
P4 Storage of potable water	Increased temperature → microbial regrowth risk	Limited storage (~1 day) → reduced safety margin	Potential overflow and contamination risk (no significant events recorded to date)	Minimal	Minimal
P5 Gravity flow to distribution	Peak demand → reduced pressure margins and possible localized pressure deficits	Reduced buffering and operational flexibility under sustained high demand	Network stress	-	-
P6 Metering	Reduced accuracy under high temperature	Increased detection difficulty under variable demand	Damage in flooded zones	-	-
W Water for consumption	Demand increase (~+21%, tourism and heat) → increased production pressure	Demand intensification → supply stress	Short-term water quality deterioration	Service disruption	Service interruption
B Brine disposal (~8700 m ³ /d)	Reduced dilution under thermal stratification	-	Dispersion variability under high flows	Outfall exposure to surge and corrosion	Wave-driven dispersion variability
S1 Power-electricity supply (~1.62 MW)	Peak electricity demand (~850–1000 MWh/month) → grid stress	Wildfire-related outage risk	Flood-related outages	Coastal substation exposure → failure risk	Wind-induced outages

Table 2. Cont.

Hazard Group	Heat Hazards (HC)	Water Scarcity Hazards (WD)	Excess Water Hazards (WF)	Coastal Hazards (C)	Wind Hazards (W)
Hazard Event	Summer Heatwave (EH)	Summer Drought (ED)	Extreme Rainfall/Flash Flood (ER)	Storm Surge/Coastal Flooding (EC)	Strong Wind (EW)
S2 Communications & control	Overheating → sensor malfunction and control instability	Higher operational reliance on control systems → greater consequences of disruption	Potential flooding of control systems → communication failure (no significant events recorded to date)	Saltwater corrosion of electronics	Signal interruption
S3 Transportation & access	Reduced safe working hours due to heat stress → limited field operations	Wildfire-related access disruption	Road erosion → delayed maintenance	Inaccessibility of coastal facilities	Transport disruption; unsafe field operations
S4 Personnel	Heat stress → reduced productivity and safety (small operational team: ~4–6 staff)	Increased operational workload	Fieldwork safety risks	Emergency response hazards	Unsafe maintenance conditions

The HWSS is particularly exposed to climate change due to its structural dependence on seawater desalination, the coastal location of critical assets, its elevated storage-based hydraulic configuration, its strong coupling with the island electricity grid, its limited storage buffering capacity ($\sim 3660 \text{ m}^3$, corresponding to approximately one day of average demand), and its high distribution losses (non-revenue water $\sim 41\%$). The examined hazard groups therefore affect the system through both direct physical impacts and indirect operational stress across its components.

Heat hazards (EH: summer heatwave) represent the dominant near-term stressor. Heatwaves coincide with seasonal demand peaks, with summer consumption ($\sim 126,000 \text{ m}^3/\text{month}$) exceeding winter demand ($\sim 104,000 \text{ m}^3/\text{month}$) by approximately 21%, increasing daily production requirements toward system capacity ($\sim 6800 \text{ m}^3/\text{d}$). Given the limited storage buffering ($\sim 3660 \text{ m}^3$, approximately 1 day of demand), the system has little capacity to absorb short-term imbalances between supply and demand. As a result, the desalination plant (A1) and associated pumping systems (P1–P3) must operate continuously at high load, increasing electricity demand (S1), which already reaches $\sim 850\text{--}1000 \text{ MWh/month}$ during summer. Elevated temperatures also accelerate chlorine decay in storage tanks and distribution pipelines (A2, A3), increasing water quality management requirements [28], while higher seawater temperatures during heatwave periods may reduce the efficiency of the reverse osmosis process and increase specific energy consumption; heat stress may also affect pumping performance (P1–P2).

Water scarcity hazards (ED: prolonged summer drought) do not directly affect source water availability (I), but they significantly intensify demand pressure and increase reliance on continuous desalination operation (A1, P2). Under these conditions, the combination of high demand and limited storage (~ 1 day autonomy) reduces system resilience, since any disruption in production rapidly translates into supply deficits. In addition, prolonged drought may affect the condition of the extensive distribution network ($\sim 75 \text{ km}$) through local ground movement or soil instability, potentially increasing leakage and exacerbating the already high non-revenue water ($\sim 41\%$), although the significance of such effects would depend on site-specific geotechnical conditions. Sustained high production levels also increase operational stress on desalination and pumping systems. Drought conditions may further increase wildfire risk, with potential impacts on electricity supply (S1), infrastructure access (S3), and overall demand pressure on the system.

Excess water hazards (ER: extreme rainfall and flash floods) are projected to intensify in the Mediterranean despite an overall decline in total precipitation [29]. Intense rainfall can cause localized flooding at desalination facilities (A1), particularly in low-elevation coastal sections ($\sim 1.5\text{--}2.0 \text{ m}$ above sea level), and may induce erosion or instability around storage tank foundations (A2). Flash flooding may damage the extensive distribution network ($\sim 75 \text{ km}$) (A3), disrupt access routes (S3), and temporarily degrade seawater quality at the intake (I), increasing pretreatment requirements (P2) and operational complexity.

Coastal hazards (EC: storm surge and sea-level rise) are critical for the HWSS due to the coastal siting of the seawater intake (I, P1) and parts of the desalination infrastructure (A1). Regional mean sea-level rise projections for the Mediterranean reach $+50 \text{ cm}$ under the moderate pathway (SSP2–4.5) and $+64 \text{ cm}$ under the high-emission pathway (SSP5–8.5) by the end of the century, while extreme total water levels may increase substantially [30]. These projections exclude low-likelihood, high-impact sea-level rise associated with rapid ice-sheet instability; however, IPCC AR6 notes that a rise approaching $\sim 2 \text{ m}$ by 2100 cannot be ruled out [31], implying greater long-term coastal risk. Infrastructure located at low elevations ($\sim 1.5\text{--}2.0 \text{ m}$) is therefore increasingly exposed to inundation, corrosion, and electrical failure during extreme events. In addition, low-lying sections of the distribution network (A3) may be affected by saline intrusion and corrosive conditions. Increased

sea surface temperature may further increase osmotic pressure and biofouling potential (P2), leading to higher energy demand and maintenance requirements [32]. To date, no significant flooding incidents from either inland runoff or coastal processes have been reported at the desalination site; however, future risk remains associated with the projected intensification of extreme events.

Wind hazards (EW: strong winds) primarily affect the system indirectly. Strong winds can disrupt electricity supply (S1), which is critical for continuous desalination operation (~1.62 MW installed power), increase wave action at intake and brine discharge locations (I, B), and limit safe access to facilities (S3), delaying maintenance and emergency response. Direct impacts on infrastructure are generally limited but may affect exposed components of the desalination plant (A1).

Overall, while the HWSS is resilient in terms of source water availability, its vulnerability arises from strong dependence on energy-intensive desalination, limited storage buffering (~1 day), high distribution losses (~41%), and coastal exposure of critical assets. Climate change is expected to amplify these structural sensitivities, particularly through combined heat–demand–energy interactions and increasing coastal risks.

3.1.3. Climate Indicators for the Hermoupolis Water Supply System

The climate exposure of the HWSS is assessed using a set of standardized climate indicators that quantify the magnitude, frequency, and intensity of the hazard events defined in Section 3.1.2. Based on internationally recognized definitions [29,31,33–35] these indicators were selected to represent the dominant climate stressors expected for the Cyclades and are briefly described below, with their linkage to system components summarized in Table 3.

Table 3. Climate indicators and affected components.

Hazard Group	Hazard Events	Climate Indicator	Affected Components
Heat hazards (HC)	EH: Summer heatwave (multi-day)	Mean daily maximum temperature	A1, A2, A3, P2, P3, P4, P5, W, S1, S2, S4
		Hot days	A1, A2, A3, P2, P3, P4, P5, W, S1, S4
		HSD	S4, S1, A1, P2, P3
		CDD	A3, W, P5, S1, S3, S4
Water scarcity hazards (WD)	ED: Summer drought (prolonged)	SPI-2	A3, W, S1, S3, S4
		SPI-1 Whiplash: Dry to Wet	A1, A2, A3, P1, P4, B, S2, S3
		SPI-1 Whiplash: Wet to Dry	A1, A2, A3, P4, W, S1, S3
Excess water hazards (WF)	ER: Extreme rainfall/flash flood	Rx1day	A1, A2, A3, P1, P4, B, S2, S3, S4
		R20mm	A1, A2, A3, P1, P4, S2, S3
Coastal hazards (C)	EC: Storm surge/coastal flooding	Δ MSL	I, A1, P1, B, S1, S3
		TWL100	I, A1, P1, B, S1, S2, S3
Wind hazards (W)	EW: High wind	WS10 > 10	I, A1, B, S1, S2, S3, S4
		WSmean	I, A1, B, S1

Heat hazards (HC) are characterized using temperature-based extreme climate indices defined by the Expert Team on Climate Change Detection and Indices (ETCCDI) [33,34,36]:

- Average summer maximum temperature (TX, °C): Mean daily maximum temperature (TX) during June–August (JJA). This indicator represents background thermal loading affecting reverse osmosis (RO) efficiency, electricity demand, and chlorine decay rates in storage tanks [29,37].
- Hot days (TX90p, days/year): Number of days when daily maximum temperature exceeds the 90th percentile of the baseline period [29,31,33]. This indicator quantifies

heatwave frequency and is directly associated with peak potable water demand during the tourism season [29].

- Heat Stress Days (HSD, days/year): Number of days exceeding a defined thermal stress threshold that is humidex $> 38^{\circ}\text{C}$; HSD is relevant for occupational exposure (S4 Personnel) and electricity demand surges affecting desalination (S1 Power supply) [34,35,37,38].
- Water scarcity hazards (WD) can be assessed using precipitation-based indices:
- Consecutive Dry Days (CDD, days): Maximum annual number of consecutive days with daily precipitation less than 1 mm in a year [29,31,33]. CDD identifies extended drought periods that intensify water demand and may increase soil shrink–swell processes affecting buried polyethylene pipes [34].
- Standardized Precipitation Index (SPI-2): A probabilistic drought index calculated over a 2-month accumulation period [35]. SPI values between -0.5 and -1.0 indicate moderate drought conditions. SPI-2 captures seasonal drought severity relevant for demand amplification and wildfire risk affecting power infrastructure.
- SPI-1 Whiplash Indicators (events/decade): Frequency of rapid transitions between dry ($\text{SPI} \leq -1$) and wet ($\text{SPI} \geq +1$) states at a 1-month scale. These indicators quantify hydroclimatic variability and compound event potential, relevant for infrastructure stress and coastal sediment dynamics [29,33].
- Excess water hazards (WF) are quantified through:
- Annual maximum 1-day precipitation (Rx1day , mm): Maximum daily precipitation amounts in a year [36]. Rx1day represents extreme rainfall intensity capable of triggering flash floods, erosion near storage tanks, and pipe exposure.
- Heavy precipitation days (R20mm , days/year): Annual number of days with precipitation ≥ 20 mm [36]. This indicator captures event frequency associated with runoff surges and short-term operational disruptions.
- These indices are widely used in IPCC AR6 and European climate assessments.
- Coastal hazards (C) are assessed using:
- Regional mean sea-level rise (ΔMSL , m): Change in mean sea level relative to the 1995–2014 baseline, consistent with IPCC AR6 methodology [29,39]. This indicator captures long-term inundation and corrosion risks affecting intake structures and desalination facilities.
- 100-year Total Water Level (TWL100 , m): Extreme coastal water level with 100-year return period, integrating mean sea level, storm surge, wave setup, and tidal contributions, with a baseline corresponding to the modelled present-day condition (2010 reference horizon) [30,40]. TWL100 is particularly relevant for the coastal siting of the desalination plant and seawater intake in Hermoupolis.

Wind hazards (W) are described using:

- $\text{WS10} > 10$ (days/year): Number of days with wind speed > 10 m/s [34,35]. This threshold captures operationally significant wind events.
- Mean wind speed (WSmean , m/s): Annual average wind speed, representing background exposure conditions.

High wind speeds are associated with structural stress, intake wave agitation, brine outfall dispersion variability, and electricity grid interruptions [29].

To support component-level exposure scoring (Step 3.1), each indicator is explicitly linked to the HWSS components, as shown in Table 3. The linkage is based on the physical and operational pathways through which the hazard influences system performance. For example, heat indicators ($\Delta\text{TX}^- \text{JJA}$, $\Delta\text{TX90p}/\text{SU35}$, ΔHSD , ΔAT) affect (i) demand-side pressure (W, A3, P5), (ii) desalination production and pumping energy requirements (A1, P2, P3) and therefore (iii) power supply vulnerability (S1), while also influencing water quality management through chlorine decay and water temperature in storage and dis-

tribution (A2, A3, P4). Dryness indicators (Δ CDD, SPI-2) do not constrain source water availability (I) but increase operational stress through demand intensification and leakage/NRW pathways in the distribution network (A3), with potential indirect effects on grid reliability (S1) and access/operations during wildfire-prone periods (S3, S4). Wet indicators (Δ Rx1day, Δ R20mm) represent flood/erosion hazards affecting coastal assets (A1, P1, B), tank sites (A2), network integrity (A3), and monitoring/repair capacity (S2–S4). Coastal indicators (Δ MSL, Δ TWL100) are critical for HWSS due to the coastal siting of seawater intake, desalination infrastructure and brine disposal (I, A1, P1, B), while wind indicators (Δ WS10 > 10, Δ WSmean) capture operational disruption and compound coastal-wave stress, with strong relevance for power and communications (S1–S2) and field operations (S3–S4). Accordingly, Table 3 summarizes the selected indicators and identifies the HWSS components for which each indicator is considered relevant for exposure assessment, ensuring transparency and consistency between Step 2 (indicator projections) and Step 3 (component exposure scoring).

3.2. Step 2 Climate Change Assessment

The second step of the assessment of climate change is performed in two substeps: 2.1 selection of the time horizons and climate scenarios, and 2.2 estimation of the values of climate indicators (selected in substep 1.3) for all selected climate scenarios (in substep 2.1).

Daily high-resolution (1 km $\times$ 1 km) statistically downscaled projections were used from four CMIP6 global climate models (GCMs), selected on the basis of the regional sub-ensemble methodology proposed by [41]: UKESM1-0-LL (r1i1p1f2) developed by the Met Office Hadley Centre (MOHC), MIROC-ES2L (r1i1p1f2) by the Center for Climate System Research (University of Tokyo), JAMSTEC, and NIES, CanESM5 (r1i1p1f1) by the Canadian Centre for Climate Modelling and Analysis, and INM-CM4-8 (r1i1p1f1) by the Russian Academy of Sciences.

These simulations were statistically downscaled within the framework of the Climadathub project (<https://www.climadathub.gr/>, accessed on 2 June 2026) using the methodology described in Varotsos et al. [42], with the CLIMADAT-GRid high-resolution (1 km $\times$ 1 km) gridded observational dataset for Greece [43] serving as the reference dataset.

For this study, daily time series corresponding to the nearest land grid point to Syros were extracted for three time slices: the reference historical period 1981–2000, the near future (short-term) period 2041–2060, and the far future (long-term) period 2081–2100. These projections were analyzed under two emission scenarios, SSP2–4.5, representing an intermediate stabilization-moderate emission-pathway, and SSP5–8.5, representing a high-emission pathway.

Table 4 shows the values of climate indicators for all scenarios and emission pathways.

Table 4. Values of climate indicators for all scenarios and emission pathways. Δ indicates the absolute changes (unless indicated otherwise) between the future and the reference periods.

Climate Indicator	Reference [1981–2000]	Near Future [2041–2060]	Far Future [2081–2100]	Near Future [2041–2060]	Far Future [2081–2100]
Emission pathway		SSP2–4.5		SSP5–8.5	
Average summer Tx (oC)	28.4	31.5 [Δ = 3.1]	32.4 [Δ = 4]	32.3 [Δ = 3.9]	34.4 [Δ = 6]
Hot days (days)	20	70 [Δ = 50]	75 [Δ = 55]	77 [Δ = 57]	86 [Δ = 66]
Heat stress days (days)	29	76 [Δ = 47]	80 [Δ = 51]	81 [Δ = 52]	88 [Δ = 59]

Table 4. Cont.

Climate Indicator	Reference [1981–2000]	Near Future [2041–2060]	Far Future [2081–2100]	Near Future [2041–2060]	Far Future [2081–2100]
CDD (days)	81	81 [$\Delta = 0$]	82 [$\Delta = 1$]	85 [$\Delta = 4$]	84 [$\Delta = 3$]
SPI-2	0.03	−0.43 [$\Delta = -0.46$]	−0.57 [$\Delta = -0.64$]	−0.83 [$\Delta = -0.86$]	−1.23 [$\Delta = -1.26$]
SPI-1 Whiplash: Dry to Wet (Events/Decade)	1.5	5.0	5.0	4.5	7.0
SPI-1 Whiplash: Wet to Dry (Events/Decade)	2.5	4.5	3.0	6.0	6.0
Rx1day (mm)	25.3	28.2 [$\Delta = 11\%$]	27.6 [$\Delta = 9\%$]	27.8 [$\Delta = 10\%$]	32 [$\Delta = 26\%$]
R20mm (days)	9	10 [$\Delta = 11$]	9 [$\Delta = 0$]	9 [$\Delta = 0$]	8 [$\Delta = -1$]
Regional mean sea-level rise (Δ MSL)	0 *	+22 cm	+50 cm	+25 cm	+64 cm
100-year Total Water Level (TWL100)	69 cm *	+26 cm	+61 cm	+29 cm	+80 cm
Wind speed > 10 (m/s)	2	3 [$\Delta = 1$]	2 [$\Delta = 0$]	2 [$\Delta = 0$]	2 [$\Delta = 0$]
Mean wind speed (m/s)	4.64	4.64 [$\Delta = 0$]	4.64 [$\Delta = 0$]	4.64 [$\Delta = 0$]	4.64 [$\Delta = 0$]

* For regional mean sea-level rise (Δ MSL), projections are expressed relative to the 1995–2014 reference period, consistent with IPCC AR6 methodology. For the 100-year Total Water Level (TWL100), the baseline corresponds to the modelled present-day condition (2010 reference horizon), representing the absolute 100-year return level at the Hermoupolis (Syros) coastal target point.

3.3. Step 3 Vulnerability Assessment

The vulnerability assessment evaluates whether projected climate stressors justify progression to risk analysis (Step 4). The methodology follows the European Commission (EC) technical guidance [12,13] and assesses vulnerability as the combined effect of exposure (E) and sensitivity (S), with adaptive capacity incorporated within sensitivity. Vulnerability is calculated as: $V = E \times S$. Both exposure and sensitivity are evaluated using a three-level ordinal scale: Low = 1, Medium = 2, High = 3. Vulnerability values therefore range from 1 to 9 and are reclassified as: Low: 1–2, Medium: 3–5, and High: 6–9. High vulnerability cases ($V \geq 6$) proceed directly to risk analysis. Medium cases are screened based on infrastructure criticality, while low cases are not advanced.

3.3.1. Exposure Analysis

Exposure reflects the magnitude of projected climate hazards under the selected scenarios (Table 4). For each hazard group, the projected indicator values are compared against the exposure thresholds defined in Table 5 and classified using the ordinal scale Low = 1, Medium = 2, High = 3. The resulting exposure scores therefore vary across scenarios, allowing the assessment to capture both temporal evolution (near vs. far future) and emission pathway sensitivity (SSP2–4.5 vs. SSP5–8.5). The resulting scenario-specific exposure scores for each component are presented in Table 6. It is noted that (i) the reference period (1981–2000) is classified as Low exposure for all hazards, and (ii) for hazard groups defined by multiple indicators (e.g., heatwaves), the highest exceedance governs the exposure classification to avoid underestimation. The exposure assessment is hazard-driven and does not depend on system characteristics, which are examined separately in the sensitivity analysis.

Table 5. Climate indicators and medium exposure thresholds relative to the baseline period.

Hazard Group	Hazard Events	Climate Indicator	Low Exposure	Medium Exposure	High Exposure	References
Heat hazards (HC)	EH: Summer heatwave (multi-day)	ΔTX^- (°C)	<1	1–2	>2	[31]
		$\Delta TX90p$ or $SU35$ (days/year)	<10	10–20	>20	[31,33]
		ΔHSD (days/year)	<10	10–20	>20	[37]
		ΔAT (°C equivalent)	<2	2–4	>4	[31,38]
Water scarcity hazards (WD)	ED: Summer drought (prolonged)	ΔCDD (days)	<10	10–20	>20	[33]
		SPI-2	>−0.5	−0.5–−1.0	<−1.0	[35]
		SPI-1 Dry→Wet (events/decade)	0–1	2–3	>3	[31]
		SPI-1 Wet→Dry (events/decade)	0–1	2–3	>3	[31]
Excess water hazards (WF)	ER: Extreme rainfall/flash flood	$\Delta Rx1day$ (%)	<5	5–15	>15	[31]
		$\Delta R20mm$ (days/year)	0–1	2–3	>3	[33]
Coastal hazards (C)	EC: Storm surge/coastal flooding	ΔMSL (m)	<0.2	0.2–0.4	>0.4	[31]
		$\Delta TWL100$ (m)	<0.2	0.2–0.6	>0.6	[30,44]
Wind hazards (W)	EW: High wind	$\Delta WS10 > 10$ (days/year)	0–1	2–3	>3	[31]
		$\Delta WSmean$ (m/s)	<0.5	0.5–1.0	>1.0	[31]

Table 6. Component exposure to hazard events. The five values in each sequence correspond, in order, to reference period (1981–2000), Near Future SSP2–4.5, Far Future SSP2–4.5, Near Future SSP5–8.5, and Far Future SSP5–8.5.

Component	Summer Heatwave (EH)	Summer Drought (ED)	Extreme Rainfall/Flash Flood (ER)	Storm Surge/Coastal Flooding (EC)	Strong Wind (EW)
I Seawater	1-1-1-1-1	1-1-1-1-1	1-2-2-2-3	1-2-3-2-3	1-1-1-1-1
A1 Desalination plant	1-3-3-3-3	1-2-2-2-3	1-2-2-2-3	1-2-3-2-3	1-1-1-1-1
A2 Storage & piping to network	1-3-3-3-3	1-2-2-2-3	1-2-2-2-3	1-1-1-1-1	1-1-1-1-1
A3 Distribution network	1-3-3-3-3	1-2-2-2-3	1-2-2-2-3	1-1-1-1-1	1-1-1-1-1
P1 Pumping of seawater	1-3-3-3-3	1-2-2-2-3	1-2-2-2-3	1-2-3-2-3	1-1-1-1-1
P2 Desalination processes	1-3-3-3-3	1-2-2-2-3	1-1-1-1-1	1-2-3-2-3	1-1-1-1-1
P3 Pumping to storage tanks	1-3-3-3-3	1-2-2-2-3	1-1-1-1-1	1-1-1-1-1	1-1-1-1-1
P4 Storage of potable water	1-3-3-3-3	1-2-2-2-3	1-2-2-2-3	1-1-1-1-1	1-1-1-1-1
P5 Gravity flow to distribution	1-3-3-3-3	1-2-2-2-3	1-1-1-1-1	1-1-1-1-1	1-1-1-1-1
P6 Metering	1-3-3-3-3	1-2-2-2-3	1-2-2-2-3	1-1-1-1-1	1-1-1-1-1
W Water for consumption	1-3-3-3-3	1-2-2-2-3	1-2-2-2-3	1-1-1-1-1	1-1-1-1-1
B Brine disposal	1-3-3-3-3	1-1-1-1-1	1-2-2-2-3	1-2-3-2-3	1-1-1-1-1
S1 Power-electricity supply	1-3-3-3-3	1-2-2-2-3	1-2-2-2-3	1-2-3-2-3	1-1-1-1-1
S2 Communications & control	1-3-3-3-3	1-1-1-1-1	1-2-2-2-3	1-2-3-2-3	1-1-1-1-1
S3 Transportation & access	1-3-3-3-3	1-2-2-2-3	1-2-2-2-3	1-2-3-2-3	1-1-1-1-1
S4 Personnel	1-3-3-3-3	1-2-2-2-3	1-2-2-2-3	1-2-3-2-3	1-1-1-1-1

In Tables 6, 8, 10 and 13, each sequence of values (e.g., 1-1-1-1-1 or 1-2-3-2-3) represents the exposure scores for the five assessment periods/scenarios in the following fixed order: reference period (1981–2000), Near Future SSP2–4.5 (2041–2060), Far Future SSP2–4.5 (2081–2100), Near Future SSP5–8.5 (2041–2060), and Far Future SSP5–8.5 (2081–2100). For example, the sequence 1-2-3-2-3 indicates Low exposure in the reference period, Medium exposure in the Near Future under SSP2–4.5, High exposure in the Far Future under SSP2–4.5, Medium exposure in the Near Future under SSP5–8.5, and High exposure in the Far Future under SSP5–8.5.

From Table 6, the following are noted:

- Exposure to heat hazards shifts from Low in the reference period to High in all future scenarios due to substantial increases in mean summer temperature, hot days, and heat stress days.
- Exposure to water scarcity hazards evolves from Low in the reference period to Medium in the near and far future under SSP2–4.5 and SSP5–8.5 and becomes High in the far future under SSP5–8.5 due to SPI-2 values below -1.0 .
- Exposure to excess water hazards increases from Low in the reference period to Medium in most future scenarios and becomes High in the far future under SSP5–8.5 due to a 26% increase in Rx1day.
- Coastal exposure progresses from Low in the baseline to Medium and High in future periods, depending on sea-level rise magnitude and projected total water levels.

Wind exposure remains Low across all scenarios due to negligible projected changes.

Overall, the exposure analysis indicates that the examined hazards (heatwaves, droughts, extreme rainfall, and coastal processes) exhibit high projected intensity under future climate scenarios, while projected changes in wind conditions remain limited. This pattern implies that vulnerability differentiation in subsequent steps will primarily depend on component sensitivity and adaptive capacity rather than differences in exposure.

3.3.2. Sensitivity Analysis

Sensitivity represents the propensity of each HWSS component to be adversely affected when exposed to a hazard, taking into account both intrinsic susceptibility and adaptive capacity, in accordance with EC technical guidance [13].

In the HWSS, sensitivity is shaped primarily by the system's dependence on continuous desalination operation (nominal capacity $\sim 6800 \text{ m}^3/\text{d}$), its strong coupling with the electricity supply system (installed power $\sim 1.62 \text{ MW}$ and specific energy consumption $\sim 7\text{--}8.5 \text{ kWh}/\text{m}^3$), its limited storage buffering capacity ($\sim 3660 \text{ m}^3$, corresponding to approximately one day of average demand $\sim 3700 \text{ m}^3/\text{d}$), and its high distribution losses (non-revenue water $\sim 41\%$). These characteristics reduce operational flexibility and increase the system's susceptibility to disruption under climate stress conditions.

Intrinsic sensitivity depends on component criticality, system interdependencies, physical fragility, and service continuity requirements. In the HWSS, critical components include the desalination plant (A1), seawater intake and pumping systems (I, P1), and the electricity supply (S1), whose continuous operation is required to maintain water production. Operational data indicate that interruptions in desalination or power supply, even for several hours (with observed events up to $\sim 11 \text{ h}$), may significantly affect system performance due to limited storage autonomy.

Adaptive capacity in the HWSS is supported to some extent by the modular configuration of desalination units and the presence of multiple pumping systems, which provide partial operational redundancy. However, this capacity remains constrained by limited storage buffering ($\sim 1 \text{ day}$), high system losses ($\sim 41\%$), and dependence on uninterrupted electricity supply, which reduce the system's ability to absorb shocks or maintain service under stress conditions.

Sensitivity (S) is evaluated using a three-level ordinal scale: Low = 1, Medium = 2, High = 3. High sensitivity ($S = 3$) is assigned to components whose malfunction would immediately disrupt water production or supply and for which effective short-term coping options are limited. In the HWSS, this includes the desalination plant (A1), seawater intake and pumping systems (I, P1), and the electricity supply (S1), reflecting the system's dependence on continuous operation. The distribution network (A3) is also highly sensitive, particularly under peak demand conditions, as high non-revenue water ($\sim 41\%$) reduces effective system capacity and amplifies pressure instability during periods of increased

demand. Medium sensitivity ($S = 2$) is assigned where impacts are significant but partially mitigated through buffering or operational measures. This includes storage tanks (A2, P4), which provide limited short-term buffering ($\sim 3660 \text{ m}^3 \approx 1 \text{ day}$), as well as components such as brine disposal (B) and communication and control systems (S2), where operational adjustments may reduce immediate impacts. Low sensitivity ($S = 1$) is assigned where structural robustness, passive operation, or limited hazard interaction reduces potential impact. Components such as gravity-driven distribution processes (P5) exhibit lower sensitivity due to reduced dependence on external inputs such as energy supply.

Overall, sensitivity in the HWSS is driven primarily by limited buffering capacity, energy dependence, and system inefficiencies rather than by source water availability. The resulting net sensitivity scores for all component–hazard combinations are presented in Table 7.

Table 7. Component sensitivity to hazard events.

Component	Summer Heatwave (EH)	Summer Drought (ED)	Extreme Rainfall/ Flash Flood (ER)	Storm Surge/Coastal Flooding (EC)	Strong Wind (EW)
I Seawater	1	1	2	3	2
A1 Desalination plant	3	2	2	3	2
A2 Storage & piping to network	2	2	2	1	1
A3 Distribution network	3	3	2	1	1
P1 Pumping of seawater	3	2	2	3	2
P2 Desalination processes	3	2	1	2	1
P3 Pumping to storage tanks	3	2	1	1	1
P4 Storage of potable water	2	2	2	1	1
P5 Gravity flow to distribution	2	2	1	1	1
P6 Metering	2	2	2	1	1
W Water for consumption	3	3	2	1	1
B Brine disposal	1	1	2	3	2
S1 Power-electricity supply	3	3	2	3	2
S2 Communications & control	2	1	2	2	2
S3 Transportation & access	2	2	2	2	2
S4 Personnel	3	2	2	2	2

3.3.3. Vulnerability Analysis

Scenario-specific vulnerability scores, calculated as $V = E \times S$, are presented in Table 8. As shown in Table 8, heatwave vulnerability becomes High already in the Near Future for most operational and energy-dependent components, including the desalination plant (A1), pumping systems (P1–P3), the distribution network (A3), potable water supply (W), the electricity supply (S1), and personnel (S4), and remains High across future scenarios. Drought vulnerability is generally Medium in the Near Future and becomes High in the Far Future under SSP5–8.5, particularly for the distribution network, gravity flow, potable water supply, and power supply components. Vulnerability to extreme rainfall remains Medium in most scenarios and becomes High mainly in the Far Future under SSP5–8.5 for the intake, desalination, pumping systems, and supporting infrastructure. Coastal vulnerability also increases over time and reaches High levels in the Far Future under both emission pathways, especially for intake structures, desalination assets, pumping systems, brine disposal, and power supply. In addition, distribution network segments located in low-elevation coastal zones exhibit increasing vulnerability due to potential saline intrusion and corrosive exposure under sea-level rise and storm surge conditions. Wind-related vulnerability remains Low in all scenarios and is therefore excluded from risk analysis.

Overall, progression to Step 4 is dominated by heatwave hazards in the Near Future and by drought, extreme rainfall, and coastal hazards in the Far Future, particularly under

SSP5–8.5. This scenario-specific screening differentiates between immediate adaptation priorities and longer-term climate risk escalation.

Table 8. Component vulnerability to hazard events. The five values in each sequence correspond, in order, to: reference period (1981–2000), Near Future SSP2–4.5, Far Future SSP2–4.5, Near Future SSP5–8.5, and Far Future SSP5–8.5.

Component	Summer Heatwave (EH)	Summer Drought (ED)	Extreme Rainfall/ Flash Flood (ER)	Storm Surge/Coastal Flooding (EC)	Strong Wind (EW)
I Seawater	1-1-1-1-1	1-2-2-2-3	2-4-4-4-6	3-6-9-6-9	2-2-2-2-2
A1 Desalination plant	3-9-9-9-9	2-4-4-4-6	2-4-4-4-6	3-6-9-6-9	2-2-2-2-2
A2 Storage & piping to network	2-6-6-6-6	2-4-4-4-6	2-4-4-4-6	1-1-1-1-1	1-1-1-1-1
A3 Distribution network	3-9-9-9-9	3-6-6-6-9	2-4-4-4-6	1-1-1-1-1	1-1-1-1-1
P1 Pumping of seawater	3-9-9-9-9	2-4-4-4-6	2-4-4-4-6	3-6-9-6-9	2-2-2-2-2
P2 Desalination processes	3-9-9-9-9	2-4-4-4-6	1-1-1-1-1	2-4-6-4-6	1-1-1-1-1
P3 Pumping to storage tanks	3-9-9-9-9	2-4-4-4-6	1-1-1-1-1	1-1-1-1-1	1-1-1-1-1
P4 Storage of potable water	2-6-6-6-6	2-4-4-4-6	2-4-4-4-6	1-1-1-1-1	1-1-1-1-1
P5 Gravity flow to distribution	2-6-6-6-6	2-4-4-4-6	1-1-1-1-1	1-1-1-1-1	1-1-1-1-1
P6 Metering	2-6-6-6-6	2-4-4-4-6	1-2-2-2-3	1-1-1-1-1	1-1-1-1-1
W Water for consumption	3-9-9-9-9	3-6-6-6-9	2-4-4-4-6	1-1-1-1-1	1-1-1-1-1
B Brine disposal	1-3-3-3-3	1-1-1-1-1	2-4-4-4-6	3-6-9-6-9	2-2-2-2-2
S1 Power-electricity supply	3-9-9-9-9	3-6-6-6-9	2-4-4-4-6	3-6-9-6-9	2-2-2-2-2
S2 Communications & control	2-6-6-6-6	1-1-1-1-1	2-4-4-4-6	2-4-6-4-6	2-2-2-2-2
S3 Transportation & access	2-6-6-6-6	2-4-4-4-6	2-4-4-4-6	2-4-6-4-6	2-2-2-2-2
S4 Personnel	3-9-9-9-9	2-4-4-4-6	2-4-4-4-6	2-4-6-4-6	2-2-2-2-2

3.3.4. WEFT-Adjusted Vulnerability Assessment

Section 3.3 presented the baseline (technical) vulnerability assessment of the HWSS using the EC-aligned formulation $V = E \times S_t$, where exposure (E) is climate-driven (Table 6) and sensitivity (S_t) reflects intrinsic susceptibility including adaptive capacity (Table 7). The resulting vulnerability values are reported in Table 8. Under the WEFT framework, exposure remains unchanged within the local scale and analytical scope of the present CRVA, because tourism is not assumed to modify the magnitude or probability of the assessed climate hazards over the study area and assessment horizon. Instead, cross-sector interactions are incorporated at the sensitivity level to account for tourism-driven seasonal demand amplification. This local-scale assumption does not imply climatic neutrality of tourism in a broader sense, as tourism also contributes to greenhouse-gas emissions and to the wider processes driving climate change, particularly in strongly transport- and aviation-dependent systems [45,46]. Accordingly, the adopted formulation preserves the computational structure of the CRVA and ensures direct comparability between the technical and WEFT-adjusted assessments [12,15,16].

Sensitivity is therefore extended as $S_{WEFT} = S_t + \Delta S$, where ΔS represents tourism-induced amplification applied selectively to summer-dominant hazards, primarily prolonged drought. In the HWSS, the dominant nexus mechanism is the coincidence of (i) summer tourism peaks and (ii) summer climate hazards, combined with the strong electricity dependence of desalination and pumping. Tourism activity in Europe exhibits marked seasonal concentration, with peak accommodation and visitor intensity occurring during July–August [20], which coincides with the period of highest heat and drought pressure in the Aegean region. At the same time, water–energy interdependence is structurally embedded in the HWSS, as water abstraction, pumping, treatment, and desalination require continuous electricity supply [26]. For Syros, case-study documentation and regional analyses identify seasonal water stress driven by tourism-related demand peaks and reliance on energy-intensive desalination, supporting the conceptual basis for introducing

“tourism amplification” in sensitivity [47]. Accordingly, sensitivity adjustments are applied conservatively and only to components directly governing production, pumping, storage buffering, and operational response. Under prolonged summer drought (E2), selected components previously classified as medium sensitivity ($S_t = 2$ in Table 7) are upgraded to high sensitivity ($S_{WEFT} = 3$). The modified values are summarized in Table 9, while all other components retain the baseline sensitivity scores shown in Table 7. Sensitivity values associated with coastal and extreme rainfall hazards remain unchanged, as their impacts are primarily governed by physical exposure rather than seasonal demand amplification.

Table 9. WEFT-adjusted technical sensitivity under prolonged summer drought conditions (only modified values shown).

Component	S_t	S_{WEFT}	Justification (Tourism Amplification Mechanism)
A1 Desalination plant	2	3	Increased production load during peak tourist demand reduces operational margin
P1 Seawater pumping	2	3	Sustained high pumping demand under drought and peak season conditions
P2 Desalination process	2	3	Continuous high utilisation increases consequence of process interruption
P3 Pumping to storage tanks	2	3	Reduced storage buffer during peak demand increases vulnerability
S4 Personnel	2	3	Higher operational pressure and reduced response flexibility in peak season

WEFT-adjusted vulnerability is calculated as $V_{WEFT} = E \times S_{WEFT}$. Because exposure values remain those presented in Table 6, differences relative to the baseline vulnerability (Table 8) arise only for drought-related component–hazard combinations where sensitivity increases. The recalculated vulnerability values are presented in Table 10. The WEFT adjustment results in several production and pumping components (A1, P1–P3) and personnel (S4) shifting from Medium to High vulnerability under drought conditions in the Near Future. In the Far Future, vulnerability remains High in both baseline and WEFT assessments, although its magnitude increases. Vulnerability classifications for heatwave, extreme rainfall, and coastal hazards remain unchanged relative to Table 8. Thus, the WEFT framework does not introduce new hazard pathways or modify exposure classifications; rather, it alters the temporal emergence of high vulnerability by increasing the number of components classified as High in earlier scenarios. From a procedural perspective, the set of hazard–component combinations advancing to risk analysis remains unchanged, but the WEFT assessment strengthens the urgency of adaptation prioritization by accelerating drought-related vulnerability.

Table 10. WEFT-adjusted vulnerability values under drought (only modified values shown). The five values in each sequence correspond, in order, to: reference period (1981–2000), Near Future SSP2–4.5, Far Future SSP2–4.5, Near Future SSP5–8.5, and Far Future SSP5–8.5.

Component	V	V_{WEFT}
A1 Desalination plant	2-4-4-4-6	3-6-6-6-9
P1 Seawater pumping	2-4-4-4-6	3-6-6-6-9
P2 Desalination process	2-4-4-4-6	3-6-6-6-9
P3 Pumping to storage tanks	2-4-4-4-6	3-6-6-6-9
S4 Personnel	2-4-4-4-6	3-6-6-6-9

3.4. Step 4 Risk Assessment

The risk assessment of the HWSS constitutes the fourth step of the CRVA methodology, which consists of the following three sub-steps: 4.1 likelihood analysis, 4.2 impact analysis, and 4.3 risk analysis; it builds directly on the vulnerability screening results of Section 3.3. Only hazard–component combinations classified as Medium or High vulnerability are advanced to risk analysis, in accordance with EC technical guidance [12,13]. Risk is evaluated through sequential assessment of likelihood (P), impact (I), and their combination. Wind hazards are excluded from risk assessment due to consistently Low vulnerability.

3.4.1. Likelihood Analysis

Likelihood (P) represents the probability of occurrence of each hazard event within the selected time horizons and emission pathways. Unlike exposure, which is component-specific, likelihood is assessed at the hazard level, as the probability of heatwaves, droughts, extreme rainfall, or coastal flooding over Syros is common to all HWSS components.

Likelihood classification is derived from the projected evolution of climate indicators (Table 4) using the same threshold logic applied in the exposure analysis. A three-level ordinal scale is adopted: Low (1), Medium (2), High (3), consistent with IPCC calibrated terminology [31] and EC guidance [12,13]. For hazard groups defined by multiple indicators, the highest exceedance governs classification. The resulting likelihood classifications are summarized in Table 11 and are used to compute risk in Section 3.4.3.

Table 11. Likelihood (P) of hazard events per scenario.

Hazard Event	Reference [1981–2000]	Near Future [2041–2060] SSP2–4.5	Far Future [2081–2100] SSP2–4.5	Near Future [2041–2060] SSP5–8.5	Far Future [2081–2100] SSP5–8.5
Summer heatwave (EH)	1	3	3	3	3
Summer drought (ED)	1	2	2	2	3
Extreme rainfall/flash flood (ER)	1	2	2	2	3
Storm surge/coastal flooding (EC)	1	2	3	2	3
Strong wind (EW)	1	1	1	1	1

From Table 11 the following are derived:

- Heatwave likelihood is High in all future scenarios. Increases in summer maximum temperature (+3.1 to +6.0 °C), hot days (+50 to +66 days), and heat-stress days (+47 to +59 days) indicate that extreme heat becomes a recurrent seasonal condition.
- Drought likelihood increases progressively. SPI-2 shifts toward moderate drought in most scenarios and reaches severe drought levels in the Far Future SSP5–8.5 [35], resulting in Medium likelihood in the Near Future and High likelihood in the Far Future under high emissions.
- Extreme rainfall likelihood rises from Low in the baseline to Medium in most future scenarios and High in the Far Future SSP5–8.5 due to intensified Rx1day projections [29].
- Coastal hazard likelihood escalates structurally with sea-level rise (+22–25 cm in the Near Future; +50–64 cm in the Far Future) and increasing total water levels [30,44]. It is therefore classified as Medium in the Near Future and High in the Far Future.

3.4.2. Impact Analysis

Impact (I) expresses the severity of consequences for each HWSS component if a hazard event occurs. Whereas likelihood reflects hazard probability, impact captures functional disruption, infrastructure damage, service degradation, economic consequences, and recovery requirements.

Impacts are assessed per component–hazard pair using the same three-level ordinal scale adopted throughout the CRVA framework:

- Low impact ($I = 1$): Minor operational disturbance, limited service degradation, no structural damage, short recovery time.
- Medium impact ($I = 2$): Noticeable service disruption, localized damage, temporary operational constraints, moderate repair or management effort.
- High impact ($I = 3$): System-critical disruption, shutdown of desalination or pumping systems, widespread supply interruption, structural damage, long recovery time, or cascading effects within the water–energy system.

In the HWSS, these impact levels are directly linked to system performance characteristics. Given that the system relies on continuous desalination production ($\sim 6800 \text{ m}^3/\text{d}$) and has limited storage buffering ($\sim 3660 \text{ m}^3$, corresponding to approximately one day of average demand $\sim 3700 \text{ m}^3/\text{d}$), interruptions in production or pumping may lead to system-wide supply deficits within a short time frame (typically less than 24 h). Therefore, hazards affecting critical components such as the desalination plant (A1), seawater intake and pumping systems (I, P1–P3), and electricity supply (S1) are generally associated with high impact.

High impacts are assigned to components whose failure would disrupt desalination production, pumping, or electricity supply, resulting in immediate or near-immediate loss of water service due to limited storage capacity. Medium impacts are assigned where impacts are significant but partially mitigated by short-term buffering or operational adjustments, such as storage tanks (A2, P4), which provide limited autonomy (~ 1 day), or communication and control systems (S2), where alternative operational responses may reduce immediate consequences. Low impacts correspond to localized or short-duration effects, typically associated with components that do not directly control production or system-wide distribution.

Heatwave impacts are highest for desalination (A1), pumping systems (P1–P3), distribution (A3), potable supply (W), power supply (S1), and personnel (S4), reflecting strong coupling between increased demand ($\sim +21\%$ in summer), continuous operation requirements, and energy consumption ($\sim 7\text{--}8.5 \text{ kWh}/\text{m}^3$). Under these conditions, system operation approaches capacity limits, increasing the severity of any disruption.

Drought impacts are significant for distribution (A3), gravity flow (P5), potable supply (W), and power supply (S1), due to sustained demand pressure and reduced operational margins. High non-revenue water ($\sim 41\%$) further amplifies these impacts by reducing effective supply capacity.

Extreme rainfall impacts concentrate on intake structures (I), desalination (A1), pumping (P1), transport (S3), and power supply (S1), where flooding or infrastructure damage may interrupt operation or access. Coastal hazards generate high impacts for intake (I), desalination (A1), pumping (P1), brine disposal (B), and power supply (S1), particularly due to the exposure of low-elevation infrastructure ($\sim 1.5\text{--}2.0 \text{ m}$) to inundation and corrosion.

Because impact represents consequence magnitude rather than probability, it is assumed constant across scenarios; scenario differentiation is introduced through likelihood. The resulting impact scores are presented in Table 12.

Table 12. Component impact (I) for hazard events.

Component	Summer Heatwave (EH)	Summer Drought (ED)	Extreme Rainfall/ Flash Flood (ER)	Storm Surge/Coastal Flooding (EC)
I Seawater	2	1	3	3
A1 Desalination plant	3	2	3	3

Table 12. Cont.

Component	Summer Heatwave (EH)	Summer Drought (ED)	Extreme Rainfall/ Flash Flood (ER)	Storm Surge/Coastal Flooding (EC)
A2 Storage & piping to network	2	2	2	1
A3 Distribution network	3	3	2	1
P1 Pumping of seawater	3	2	3	3
P2 Desalination processes	3	2	1	3
P3 Pumping to storage tanks	3	2	1	1
P4 Storage of potable water	2	2	2	1
P5 Gravity flow to distribution	2	3	1	1
P6 Metering	2	1	1	1
W Water for consumption	3	3	2	1
B Brine disposal	2	1	2	3
S1 Power-electricity supply	3	3	3	3
S2 Communications & control	2	1	2	2
S3 Transportation & access	2	2	3	2
S4 Personnel	3	2	2	2

3.4.3. Risk Analysis

Technical risk (R_t) is calculated using the multiplicative formulation consistent with IPCC and EC guidance [13]:

$$R_t = P \times I \quad (3)$$

Risk values range from 1 to 9 and are classified as: Low: 1–2, Medium: 3–5 and High: 6–9. Risk is computed for each scenario using likelihood values from Table 11 and impact scores from Table 12. Results are presented in Table 13. The results reveal a clear temporal structure:

- Heatwave risk is High already in the Near Future for most production and energy-dependent components and remains High across scenarios. Heat stress therefore constitutes the dominant near-term risk driver.
- Drought risk increases progressively and reaches High levels in the Far Future under SSP5–8.5, particularly for distribution, potable supply, gravity flow, and power supply.
- Extreme rainfall risk becomes High mainly in the Far Future high-emission scenario.
- Coastal risk escalates structurally and reaches High levels in the Far Future under both emission pathways.

Table 13. Component risk for hazard events. The five values in each sequence correspond, in order, to: reference period (1981–2000), Near Future SSP2–4.5, Far Future SSP2–4.5, Near Future SSP5–8.5, and Far Future SSP5–8.5.

Component	Summer Heatwave (EH)	Summer Drought (ED)	Extreme Rainfall/ Flash Flood (ER)	Storm Surge/Coastal Flooding (EC)
I Seawater	2-6-6-6-6	1-2-2-2-3	3-6-6-6-9	3-6-9-6-9
A1 Desalination plant	3-9-9-9-9	2-4-4-4-6	3-6-6-6-9	3-6-9-6-9
A2 Storage & piping to network	2-6-6-6-6	2-4-4-4-6	2-4-4-4-6	1-2-3-2-3
A3 Distribution network	3-9-9-9-9	3-6-6-6-9	2-4-4-4-6	1-2-3-2-3
P1 Pumping of seawater	3-9-9-9-9	2-4-4-4-6	3-6-6-6-9	3-6-9-6-9
P2 Desalination processes	3-9-9-9-9	2-4-4-4-6	1-2-2-2-3	3-6-9-6-9
P3 Pumping to storage tanks	3-9-9-9-9	2-4-4-4-6	1-2-2-2-3	1-2-3-2-3
P4 Storage of potable water	2-6-6-6-6	2-4-4-4-6	2-4-4-4-6	1-2-3-2-3
P5 Gravity flow to distribution	2-6-6-6-6	3-6-6-6-9	1-2-2-2-3	1-2-3-2-3

Table 13. Cont.

Component	Summer Heatwave (EH)	Summer Drought (ED)	Extreme Rainfall/ Flash Flood (ER)	Storm Surge/Coastal Flooding (EC)
P6 Metering	2-6-6-6-6	1-2-2-2-3	1-2-2-2-3	1-2-3-2-3
W Water for consumption	3-9-9-9-9	3-6-6-6-9	2-4-4-4-6	1-2-3-2-3
B Brine disposal	2-6-6-6-6	1-2-2-2-3	2-4-4-4-6	3-6-9-6-9
S1 Power-electricity supply	3-9-9-9-9	3-6-6-6-9	3-6-6-6-9	3-6-9-6-9
S2 Communications & control	2-6-6-6-6	1-2-2-2-3	2-4-4-4-6	2-4-6-4-6
S3 Transportation & access	2-6-6-6-6	2-4-4-4-6	3-6-6-6-9	2-4-6-4-6
S4 Personnel	3-9-9-9-9	2-4-4-4-6	2-4-4-4-6	2-4-6-4-6

Thus, risk evolution reflects both immediate thermal stress and long-term hydrometeorological and coastal intensification. This technical assessment treats the HWSS as a bounded infrastructure system in which risk differentiation arises from projected hazard likelihood interacting with intrinsic component consequences.

3.4.4. WEFT-Adjusted Risk Assessment

The WEFT framework extends the technical risk assessment by incorporating tourism-driven consequence amplification while preserving the same computational structure. Hazard likelihood (P) remains unchanged, as tourism does not affect the probability of climate hazards. Adjustments are therefore introduced at the impact level, reflecting increased consequence severity under peak demand conditions.

WEFT-adjusted risk is therefore defined as:

$$R_{WEFT} = P \times I_{WEFT} \quad (4)$$

where I_{WEFT} represents the impact modified by tourism-driven demand amplification.

Tourism amplification primarily affects prolonged summer drought, where peak visitor demand coincides with high desalination utilization and limited storage buffering [20,21,26]. Under these conditions, disruption of production or pumping systems produces more severe service and economic consequences than under baseline demand. In the HWSS, this effect is quantitatively reflected in seasonal demand patterns. Summer water consumption ($\sim 126,000 \text{ m}^3/\text{month}$) exceeds winter demand ($\sim 104,000 \text{ m}^3/\text{month}$) by approximately 21%. This increase coincides with periods of maximum climatic stress (heatwaves and droughts), during which the system operates continuously near its nominal production capacity ($\sim 6800 \text{ m}^3/\text{d}$). At the same time, storage capacity is limited ($\sim 3660 \text{ m}^3$), corresponding to approximately one day of average demand ($\sim 3700 \text{ m}^3/\text{d}$). As a result, the system operates with reduced operational margin during peak summer conditions. The combination of increased demand ($\sim +21\%$), high energy requirements ($\sim 7\text{--}8.5 \text{ kWh}/\text{m}^3$), and limited storage buffering reduces the system's ability to absorb disruptions. Consequently, interruptions in desalination production or pumping systems propagate more rapidly into system-wide supply deficits, typically within less than 24 h.

Accordingly, for prolonged summer drought (E2), selected components governing production and operational response—namely the desalination plant (A1), seawater pumping (P1), desalination processes (P2), pumping to storage (P3), and personnel (S4)—experience increased consequence severity under WEFT conditions. For these components, impact values are conservatively upgraded from Medium ($I = 2$) to High ($I_{WEFT} = 3$), reflecting the reduced tolerance of the system to disruption during peak demand periods. The modified impact values are presented in Table 14, while all other impact values remain unchanged from the technical assessment.

Table 14. WEFT-adjusted impact under prolonged summer drought (only modified values shown).

Component	<i>I</i>	<i>I</i> _{WEFT}	Justification (Tourism Amplification Mechanism)
A1 Desalination plant	2	3	Interruption during peak tourist demand causes larger service and economic impact
P1 Seawater pumping	2	3	Reduced production margin under high demand increases consequence severity
P2 Desalination process	2	3	Continuous high utilisation increases disruption impact
P3 Pumping to storage tanks	2	3	Lower storage autonomy during peak demand
S4 Personnel	2	3	Higher operational pressure and reduced response flexibility in peak season

Power supply (S1) is not modified, as its impact is already classified as High ($I = 3$) in the technical assessment due to its critical role in continuous desalination operation. Similarly, coastal and extreme rainfall hazards are not adjusted, as their impacts are governed primarily by physical exposure rather than seasonal demand amplification. The resulting WEFT-induced risk transitions are summarized in Table 15. Under Near Future scenarios ($P = 2$), several components shift from Medium risk ($R = 4$) to High risk ($R_{WEFT} = 6$) when tourism amplification is considered. Under the Far Future high-emission scenario ($P = 3$), risk magnitude increases within the High category ($R = 6$ to $R_{WEFT} = 9$).

Table 15. WEFT-induced risk transition under drought.

Component	Near Future [2041–2060] SSP2–4.5	Far Future [2081–2100] SSP2–4.5	Near Future [2041–2060] SSP5–8.5	Far Future [2081–2100] SSP5–8.5
A1 Desalination plant	4→6	4→6	4→6	6→9
P1 Seawater pumping	4→6	4→6	4→6	6→9
P2 Desalination process	4→6	4→6	4→6	6→9
P3 Pumping to storage tanks	4→6	4→6	4→6	6→9
S4 Personnel	4→6	4→6	4→6	6→9

Overall, the WEFT framework does not introduce new hazard pathways or modify hazard likelihood. Instead, it alters the timing and concentration of high-risk conditions by increasing consequence severity under peak demand periods. In the HWSS, this leads to the earlier emergence of High-risk classifications for drought-related hazards, driven by the interaction between climate stress, tourism-driven demand amplification, and strong water–energy coupling.

3.5. Step 5 Assessment of Adaptation Measures

The risk assessment (Section 3.4) identified heatwaves as the dominant near-term risk driver for the HWSS, while drought, extreme rainfall, and coastal flooding intensify toward the Far Future. Under the WEFT-adjusted assessment, drought-related risks emerge earlier due to tourism-driven demand amplification.

Adaptation measures are identified to reduce the vulnerability and risk of the HWSS under current and projected climate conditions. These measures are structured according to the Climate-ADAPT Key Types of Measures (KTM) framework [12,13], ensuring consistency with European adaptation policy while allowing system-specific prioritization.

In the HWSS, adaptation priorities are shaped by the system's dependence on energy-intensive desalination, limited storage buffering, high distribution losses, and the exposure of critical infrastructure to coastal and climatic hazards. Measures are therefore evaluated

not only in terms of general resilience improvement, but also in terms of their ability to reduce operational stress, increase buffering capacity, and address the coupled water–energy–tourism pressures identified in the WEFT framework.

To ensure methodological consistency with EU adaptation policy practice, adaptation measures are organized according to the Climate-ADAPT Key Type Measures (KTM) classification system [48], which structures adaptation actions into five standardized categories: (1) physical and technological measures, (2) Nature-Based Solutions (NBS) and ecosystem-based approaches, (3) knowledge and behavioural change approaches, (4) governance and institutional measures, and (5) economic and finance measures. This typologized approach allows transparent communication of adaptation priorities and facilitates future benchmarking against other Mediterranean island systems.

In the next paragraphs these adaptation measures are presented as Immediate/Short-Term (0–5 years), Medium-Term (5–15 years) and Long-Term (15+ years).

3.5.1. Physical and Technological Measures

Physical and technological measures aim to enhance the structural robustness and operational reliability of the HWSS, with particular emphasis on reducing dependence on external electricity supply. This priority arises directly from the strong water–energy coupling identified in the WEFT-adjusted assessment and from the dominance of heatwaves as the main near-term risk driver. Given that desalination operates at a nominal capacity of $\sim 6800 \text{ m}^3/\text{d}$ with specific energy consumption of $\sim 7\text{--}8.5 \text{ kWh}/\text{m}^3$, system performance is highly sensitive to electricity availability and peak demand conditions.

In the near term, the integration of renewable energy sources, particularly photovoltaic (PV) coupling with desalination, constitutes a key adaptation measure. Hybridization with on-site PV generation, complemented by energy storage systems, can reduce grid dependency, mitigate peak-load stress during extreme heat events, and enhance operational autonomy under combined drought and tourism-driven demand conditions. This is especially important given the observed seasonal demand increase ($\sim +21\%$) and the limited storage buffering ($\sim 3660 \text{ m}^3$, corresponding to approximately one day of demand), which reduce the system's capacity to absorb short-term disruptions.

In the medium term, increasing effective storage capacity and optimizing the operation of existing tanks can improve system buffering and reduce vulnerability to short-duration supply interruptions. Given the current storage autonomy (~ 1 day), even moderate increases in storage volume would enhance system resilience. Additional measures include introducing redundancy in critical pumping systems (P1–P3), flood-proofing electrical and control equipment, protecting seawater intake structures against debris loading and wave action, and systematically inspecting and maintaining low-elevation distribution network segments vulnerable to leakage and saline intrusion. These measures address vulnerabilities identified under extreme rainfall and coastal hazard scenarios.

In the long term, progressively intensifying coastal hazards require structural adaptation of critical infrastructure. This includes elevation or flood protection of desalination units located at low elevations ($\sim 1.5\text{--}2.0 \text{ m}$), reinforcement or redesign of seawater intake and brine outfall systems, and targeted upgrading or replacement of distribution pipelines and fittings in shoreline areas exposed to saline intrusion and corrosion. Continued expansion of renewable energy integration, combined with energy storage systems, is essential to further reduce dependence on grid reliability and address the structural water–energy interdependence identified in the WEFT assessment [26].

3.5.2. Nature-Based Solutions and Ecosystem-Based Approaches

Although the HWSS relies primarily on desalination and engineered infrastructure, nature-based solutions (NBS) can complement structural adaptation by reducing exposure and moderating demand-related pressures. Their role is supportive rather than primary, but they can contribute to system resilience through both physical buffering and indirect demand management.

In coastal areas, restoration or preservation of natural buffers, such as dunes and vegetated shorelines, can help reduce wave energy, erosion, and flood impacts on exposed infrastructure, particularly for low-elevation components of the desalination system and intake structures (~1.5–2.0 m). Such measures become increasingly relevant under projected sea-level rise and intensification of coastal hazards.

In urban areas, green infrastructure interventions, including tree planting, shading, and permeable surfaces, can mitigate local heat-island effects. This is relevant in the HWSS context, where heatwaves coincide with peak demand periods and contribute to a seasonal increase in water consumption (~+21%). By reducing ambient temperatures, such measures may indirectly moderate peak water demand and associated energy consumption for desalination.

Where local wastewater treatment conditions and hydrogeological suitability permit, treated wastewater reuse and, potentially, managed aquifer recharge could provide additional long-term resilience by enhancing local water retention and buffering capacity. However, given the system's structural dependence on desalination and limited natural freshwater resources, the contribution of such measures is expected to remain supplementary and was not assessed in detail in the present study.

Overall, while nature-based solutions play a secondary role compared with technological and infrastructure-based interventions in the HWSS, they can provide important co-benefits, including biodiversity enhancement, landscape protection, and improved social acceptance of adaptation strategies.

3.5.3. Knowledge and Behavioral Change Approaches

Behavioural and knowledge-based measures are particularly important in the HWSS, as the WEFT-adjusted assessment shows that tourism-driven demand amplification is a key driver of drought risk. Unlike supply-side interventions, these measures directly target the seasonal increase in water consumption (~+21%), which coincides with peak climatic stress and limited system buffering (~1 day of storage). In addition to tourism-oriented demand management, water-saving measures targeting permanent residents can also contribute to reducing baseline system load, particularly when combined with leakage reduction and improved water-use efficiency.

In the near term, priority actions include seasonal water conservation campaigns targeting visitors, the development and dissemination of water-efficiency guidelines for hotels and short-term rentals, and real-time public communication during drought alerts. These measures aim to reduce peak demand during critical periods, thereby alleviating pressure on desalination production and associated energy consumption. In addition, targeted training programs for operational staff under extreme heat conditions can improve response capacity and reduce system vulnerability during high-stress events.

In the medium term, the integration of digital decision-support tools, such as dashboards linking climate indicators (e.g., heatwave duration, drought indices) with operational thresholds, can enable proactive demand management and earlier intervention. Further, disaggregation of water consumption data by sector (e.g., residential versus tourism-related uses) would support more targeted behavioural measures, improve performance monitoring, and allow benchmarking of water-use efficiency across user groups.

Overall, these measures reduce vulnerability not by increasing supply capacity, but by moderating seasonal demand peaks and improving system responsiveness under combined climate and tourism pressures. In the HWSS, where limited storage ($\sim 3660 \text{ m}^3$) and high energy dependence constrain operational flexibility, demand-side management is therefore a critical component of effective adaptation.

Beyond water-saving behaviour within the existing tourism model, adaptation may also involve measures that influence tourism pressure itself. These may include activities and incentives that reduce the concentration of visitor demand during the critical summer period, encourage seasonal redistribution of tourism activity, and promote less water- and energy-intensive forms of tourism. Such pathways were not explicitly modelled in the present baseline assessment, but they are relevant in principle because they may reduce the coincidence between peak climatic stress and peak tourism-driven demand.

3.5.4. Governance and Institutional Measures

Governance measures institutionalize climate adaptation within planning and operational processes, ensuring that identified risks are systematically addressed over time. In the HWSS, governance plays a critical role in coordinating responses to the coupled water–energy–tourism pressures identified in the WEFT assessment, particularly under peak demand conditions.

In the near term, priority actions include the formalization of seasonal drought contingency plans, integration of WEFT considerations into municipal water management strategies, and the establishment of coordination protocols between the water utility and the electricity provider. Such coordination is essential given the system's dependence on continuous desalination ($\sim 6800 \text{ m}^3/\text{d}$) and electricity supply ($\sim 7\text{--}8.5 \text{ kWh}/\text{m}^3$), especially during periods of peak demand and heat stress.

In the medium term, governance measures should focus on embedding efficiency and resilience within institutional practice. This includes the introduction of regulatory requirements for water-efficient tourism facilities, the incorporation of climate risk screening into infrastructure planning and upgrades, and the establishment of formal targets for reducing non-revenue water ($\sim 41\%$). These measures directly address key structural vulnerabilities of the HWSS, including high distribution losses and limited operational flexibility.

In the long term, governance frameworks should incorporate projected sea-level rise and extreme coastal water levels into land-use planning and infrastructure siting decisions [29,30,44]. Strategic planning should prioritize the protection or relocation of critical infrastructure located in low-elevation coastal zones ($\sim 1.5\text{--}2.0 \text{ m}$). In addition, the development of integrated water–energy planning mechanisms at the regional scale would support coordinated management of interdependencies identified in the WEFT framework, improving system resilience under future climate and demand conditions.

3.5.5. Economic and Finance Measures

Economic instruments provide incentives that reinforce both technological and behavioural adaptation pathways, enabling the translation of risk awareness into concrete action. In the HWSS, such instruments are particularly relevant for addressing tourism-driven demand amplification ($\sim +21\%$ in summer) and supporting investments that reduce energy dependence and system vulnerability.

In the short-term, targeted financial incentives can support demand-side management. These include subsidies for water-efficient appliances and fixtures in tourism facilities, financial support for leakage reduction programs addressing high non-revenue water ($\sim 41\%$), and seasonal pricing structures that reflect water scarcity conditions. Such measures can

moderate peak demand during drought periods, thereby reducing pressure on desalination production ($\sim 6800 \text{ m}^3/\text{d}$) and associated energy consumption ($\sim 7\text{--}8.5 \text{ kWh}/\text{m}^3$).

In the medium term, dedicated financing mechanisms are required to support capital-intensive investments, particularly the integration of renewable energy sources and energy storage systems. These investments directly address the structural dependence of the HWSS on electricity supply and reduce vulnerability to peak-load stress during heatwaves and high-demand periods.

In the long term, large-scale adaptation measures—such as coastal protection, elevation of low-lying infrastructure ($\sim 1.5\text{--}2.0 \text{ m}$), and strategic network upgrades—will require access to resilience-oriented financing instruments. These may include EU co-financing schemes, climate adaptation funds, or innovative mechanisms such as climate bonds. Such instruments are essential to support investments that exceed the financial capacity of local utilities but are necessary to address progressively intensifying coastal and climate risks.

3.5.6. Integrated Adaptation Sequencing and Data Needs

The KTM-based classification highlights that adaptation of the HWSS must follow a staged and coordinated implementation pathway, reflecting both the temporal evolution of climate risks and the structural characteristics of the system. Immediate measures focus primarily on operational optimization, demand management, and reduction of non-revenue water ($\sim 41\%$), directly addressing the WEFT-amplified near-term risks associated with heatwaves and drought. These actions aim to reduce peak demand pressures ($\sim +21\%$) and improve system efficiency without requiring major infrastructure investments.

Medium-term actions target the enhancement of system buffering and operational redundancy. In the HWSS, this includes increasing effective storage capacity (currently $\sim 3660 \text{ m}^3$, corresponding to approximately one day of demand), improving hydraulic performance, and strengthening critical pumping and energy supply systems. These measures increase the system's ability to absorb short-duration disruptions and reduce sensitivity to combined demand–energy stress.

Long-term measures address structurally escalating risks, particularly those associated with coastal exposure. This includes the protection, elevation, or relocation of critical infrastructure located at low elevations ($\sim 1.5\text{--}2.0 \text{ m}$), as well as strategic upgrades of intake, desalination, and distribution components. Such measures are required to respond to projected sea-level rise and increasing extreme coastal water levels.

At the current stage, adaptation measures are identified qualitatively based on the risk screening results. To refine prioritization and support cost-effectiveness appraisal consistent with EC guidance [12,13], additional system-specific data are required. These include seasonal demand disaggregation (particularly tourism-related demand), high-resolution electricity load profiles for desalination operation, hydraulic modelling of storage performance under peak stress conditions, and detailed coastal inundation mapping for the desalination site and associated infrastructure.

The integration of these data would support the development of a multi-criteria evaluation framework, enabling more robust sequencing of adaptation measures and more effective allocation of financial resources. Such an approach is essential for moving from qualitative risk assessment to implementation-oriented adaptation planning in desalination-dependent, tourism-driven island systems.

4. Discussion

The present study developed and applied a structured CRVA framework to the HWSS and extended it through explicit integration of the Water–Energy–Food–Tourism (WEFT) nexus. The comparison between the technically bounded assessment and the WEFT-

adjusted assessment provides both methodological and policy-relevant insights for climate-resilient planning in Mediterranean island systems.

Under the technical risk framework, risk escalation follows a hazard-driven trajectory. Heatwaves emerge as the dominant near-term risk driver due to the strong coupling between desalinated water production, electricity demand, and their concurrent summer peaking. Drought, extreme rainfall, and coastal flooding risks intensify progressively toward the Far Future, particularly under SSP5–8.5, reflecting projected precipitation variability and sea-level rise [29–31,44]. In this configuration, risk differentiation is primarily controlled by projected hazard likelihood interacting with intrinsic infrastructure consequences.

When the WEFT nexus is incorporated, the structure of risk expression changes in a conceptually important way. Hazard likelihood remains unchanged; climate forcing is identical. However, consequence severity increases under prolonged summer drought due to tourism-driven demand amplification coinciding with peak heat conditions. Several component–hazard combinations shift from Medium to High risk already in the Near Future. The nexus perspective therefore accelerates the temporal emergence of high-risk conditions without introducing new hazards. This distinction is analytically significant: risk under WEFT is not redefined by new climatic processes, but by socio-economic amplification mechanisms embedded within the system.

This finding demonstrates that climate risk in desalination-dependent islands cannot be fully understood through infrastructure exposure alone. In Mediterranean island contexts, demand is highly seasonal and tourism-driven [20,21]. Consequently, system stress results from the interaction between climatic intensification and socio-economic concentration of demand. In this study, tourism is operationalized as an intrinsic socio-economic system component through its effect on seasonal demand amplification; however, this does not imply that tourism pressure is immutable, since its magnitude and temporal concentration may also be influenced by governance, behavioural, and strategic adaptation measures. The WEFT framework captures this compound dynamic explicitly by modifying sensitivity and impact rather than hazard probability, thereby preserving methodological transparency within the CRVA structure. This also has implications for the food dimension of island systems, because food provisioning and food-service activities depend on the same water and energy services that are stressed during peak tourist periods. In this sense, the inclusion of “F” in WEFT is not intended to introduce a separate food-infrastructure model in the present case study, but to acknowledge that climate-related disruption of water and energy systems can cascade into food availability and service reliability in tourism-dependent island economies. These findings highlight the importance of integrating tourism into climate risk assessments, even in systems with moderate seasonal demand variability, as nexus interactions can significantly influence the timing and severity of risk.

A second key contribution of the study lies in linking WEFT-based risk assessment to the Climate-ADAPT Key Type Measures (KTM) typology. While nexus-based assessments have increasingly emphasized cross-sectoral interdependencies [15,16], they are often not systematically aligned with the policy instruments used by EU Member States to categorize adaptation actions. By organizing adaptation measures under the KTM framework, the study establishes a direct bridge between scientific risk analysis and EU adaptation policy architecture. This alignment enhances comparability, supports standardized reporting, and facilitates integration of island-level planning into broader European adaptation strategies.

Importantly, KTM-based structuring reveals that resilience in desalination-dependent island systems requires a balanced portfolio of interventions. Physical and technological measures remain essential, particularly for long-term coastal exposure and energy-system coupling. However, the WEFT-adjusted results demonstrate that knowledge, behavioural, governance, and economic instruments are equally critical in the near term. Demand

management, institutional coordination, and pricing mechanisms directly address the tourism amplification pathway identified in the WEFT assessment. Without such measures, structural reinforcement alone may not prevent near-term risk escalation and could even lead to maladaptation through over-reliance on supply expansion.

The combined WEFT-KTM framework therefore advances adaptation planning in two ways. First, it improves diagnostic accuracy by revealing how socio-economic interdependencies accelerate risk timing. Second, it enhances policy operability by categorizing measures within a standardized EU framework. The methodological innovation is thus dual: integration of tourism as a structural nexus component within CRVA, and systematic translation of risk findings into KTM-aligned adaptation pathways.

From a broader perspective, the case study of Syros reflects structural characteristics common across many Mediterranean islands: desalination dependence, strong tourism seasonality, coastal siting of critical infrastructure, and limited freshwater alternatives. The WEFT-KTM approach is therefore transferable to other island systems facing compound climate and socio-economic pressures. A further extension of the present framework could examine alternative tourism-seasonality scenarios, including partial redistribution of visitor demand away from the summer peak, as a potentially relevant adaptation pathway for reducing climate-risk concentration during the most critical period. The choice of Syros as a case study is particularly informative in this context. Unlike highly tourism-intensive islands such as Mykonos or Paros, Syros exhibits moderate seasonal demand variability (peak-to-mean ratio ≈ 1.21), reflecting its more balanced socio-economic structure and year-round population. As a result, tourism-driven demand amplification in the HWSS is present but not extreme. Nevertheless, the WEFT-adjusted assessment still produces measurable shifts in vulnerability and risk classification, particularly for drought-related hazards in the near future. This demonstrates that the proposed WEFT-CRVA framework is sufficiently sensitive to detect systemic amplification effects even under moderate tourism pressure. In more tourism-intensive island systems, where seasonal demand fluctuations are significantly higher, the magnitude and timing of risk amplification are expected to be substantially greater.

Finally, the analysis underscores that infrastructure resilience in island contexts must be evaluated as a socio-technical system rather than as an isolated engineering asset. Climate change interacts with energy dependency, tourism dynamics, governance capacity, and financial instruments. Ignoring these interdependencies risks underestimating near-term drought vulnerability and mis-sequencing adaptation investments. The WEFT-KTM integration presented here provides a structured and transparent mechanism for avoiding such underestimation and for aligning scientific assessment with policy implementation pathways.

5. Conclusions

This study extends the Water–Energy–Food (WEF) nexus to Water–Energy–Food–Tourism (WEFT) by explicitly incorporating tourism as a structural demand driver within a Climate Risk and Vulnerability Assessment (CRVA) framework for desalination-dependent Mediterranean island systems. Using the HWSS on Syros (Greece) as a case study, an EC-aligned CRVA methodology was first applied under a technically bounded perspective and then adjusted to incorporate cross-sector interactions associated with tourism and energy dependence. Within this framing, the food dimension is represented as a dependent service domain linked to water and energy availability, particularly through tourism-related food provisioning and hospitality activities. Thus, although the technical assessment boundary remains centered on the water supply system, the WEFT perspective captures how disruptions in water and energy services may propagate to food-related socio-economic functions during periods of peak seasonal demand.

The technical assessment identified heatwaves as the dominant near-term climate risk driver, mainly due to the strong coupling between desalination production, electricity demand, and peak summer consumption. Drought, extreme rainfall, and coastal flooding intensify toward the Far Future, particularly under high-emission scenarios, while coastal exposure emerges as a structurally important long-term risk for critical assets located near the shoreline.

When tourism-driven amplification is incorporated, hazard likelihood remains unchanged, but consequence severity increases under prolonged summer drought because seasonal demand concentration coincides with peak climatic stress. As a result, several operational and production components shift from Medium to High risk already in the Near Future. This shows that climate risk in island systems is shaped not only by hazard intensification but also by socio-economic demand concentration and systemic interdependencies.

Methodologically, the study demonstrates that tourism-driven amplification can be incorporated without altering the computational logic of established CRVA frameworks. The methodological novelty therefore lies not in the development of a new CRVA framework, but in the operational insertion of tourism-driven amplification into the sensitivity and impact dimensions of an existing CRVA structure. In particular, hazard exposure and likelihood remain climate-driven, while cross-sector amplification effects are incorporated at the sensitivity and impact levels. This preserves comparability between the technically bounded and WEFT-adjusted assessments and allows differences in vulnerability and risk to be attributed directly to tourism- and energy-coupling effects rather than to changes in the assessment framework itself.

A second key contribution lies in the structured translation of risk results into adaptation pathways aligned with the Climate-ADAPT Key Type Measures (KTM) typology. By organizing adaptation options under standardized EU policy categories, the study links scientific risk assessment with European adaptation policy architecture and supports integration of island-level adaptation planning into broader EU resilience strategies.

From an adaptation perspective, the proposed framework modifies prioritization rather than hazard typology. While structural reinforcement and coastal protection remain essential long-term strategies, near-term resilience depends equally on demand-side governance, energy–water integration, and reduction of non-revenue water. The staged adaptation sequencing proposed in this study—immediate operational and demand measures, medium-term buffering and redundancy enhancement, and long-term coastal protection—provides a coherent pathway for climate-resilient development.

Overall, the proposed framework advances climate risk assessment for Mediterranean islands by combining explicit treatment of tourism as a structural demand amplifier, preservation of established CRVA methodological rigor, and policy-aligned categorization of adaptation measures. In spatially constrained island environments where climate hazards coincide with seasonal socio-economic pressures, such an integrated approach is essential for timely and implementable adaptation planning.

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References

1. Stamou, A.I. Hydro-Environment Research on Climate Change Adaptation of Water Infrastructure (WI). In Proceedings of the 8th IAHR Europe Congress, Lisbon, Portugal, 4–7 June 2024.
2. Stamou, A.I.; Mitsopoulos, G.; Koutroulis, A. Proposed Methodology for Climate Change Adaptation of Water Infrastructures in the Mediterranean Region. *Environ. Process.* **2024**, *11*, 12. [\[CrossRef\]](#)
3. Stamou, A.I. The Typologization of Water Research as a Possible Means to Improve the Technical Guidelines on the Adaptation of Water Infrastructure to Climate Change. *Hydrolink* **2024**, *3*, 04–08.
4. Stamou, A.I.; Mitsopoulos, G.; Sfetsos, A.; Stamou, A.T.; Varotsos, K.V.; Giannakopoulos, C.; Koutroulis, A. Typologizing the Hydro-Environmental Research on Climate Change Adaptation of Water Infrastructure in the Mediterranean Region. *Atmosphere* **2024**, *15*, 1526. [\[CrossRef\]](#)
5. Leivadiotis, E.; Farsirotou, E.; Tzoraki, O.; Kohnová, S.; Psilovikos, A. Understanding Flash Droughts in Greece: Implications for Sustainable Water and Agricultural Management. *Land* **2025**, *14*, 2290. [\[CrossRef\]](#)
6. Katsora, C.; Leivadiotis, E.; Papadopoulou, N.; Monioudi, I.; Kostopoulou, E.; Gaganis, P.; Psilovikos, A.; Tzoraki, O. Flash Drought Assessment: Insights from a Selection of Mediterranean Islands, Greece. *Hydrology* **2025**, *12*, 308. [\[CrossRef\]](#)
7. Kourtis, I.M.; Kotsifakis, K.G.; Feloni, E.G.; Baltas, E.A. Sustainable Water Resources Management in Small Greek Islands under Changing Climate. *Water* **2019**, *11*, 1694. [\[CrossRef\]](#)
8. Stamou, A.I.; Xanthopoulou, I.; Mitsopoulos, G.; Tzanes, G.; Koutroulis, A.; Stamou, A.T. Water Supply Challenges in the Aegean Islands under Climate Change. In Proceedings of the International Symposium & Workshop “Sustainable Solutions at Times of Transition (SUST 2025)”, Nisyros, Greece, 15–17 September 2025.
9. Tzanes, G.; Zafirakis, D.; Makropoulos, C.; Kaldellis, J.K.; Stamou, A.I. Energy Vulnerability and the Exercise of a Data-Driven Analysis Protocol: A Comparative Assessment on Power Generation Aspects for the Non-Interconnected Islands of Greece. *Energy Policy* **2023**, *177*, 113515. [\[CrossRef\]](#)
10. Rico-Amoros, A.M.; Olcina-Cantos, J.; Sauri, D. Tourist Land Use Patterns and Water Demand: Evidence from the Western Mediterranean. *Land Use Policy* **2009**, *26*, 493–501. [\[CrossRef\]](#)
11. Drobinski, P.; Rivera-Ferre, M.G.; Abdel Monem, M.; Driouech, F.; Cramer, W.; Guiot, J.; Gattacceca, J.C.; Marini, K. (Eds.) *Interlinking Climate Change with the Water-Energy-Food-Ecosystems (WEFE) Nexus in the Mediterranean Basin*; MedECC Reports; MedECC Secretariat: Marseille, France, 2024; ISBN 978-2-493662-09-5.
12. European Commission Directorate General for Climate Action. *EU-Level Technical Guidance on Adapting Buildings to Climate Change*; European Commission Directorate-General for Climate Action: Brussels, Belgium, 2023.
13. European Commission. *Technical Guidance on the Climate Proofing of Infrastructure in the Period 2021–2027*; European Commission: Brussels, Belgium, 2021.
14. Bazilian, M.; Rogner, H.; Howells, M.; Hermann, S.; Arent, D.; Gielen, D.; Steduto, P.; Mueller, A.; Komor, P.; Tol, R.S.J.; et al. Considering the Energy, Water and Food Nexus: Towards an Integrated Modelling Approach. *Energy Policy* **2011**, *39*, 7896–7906. [\[CrossRef\]](#)
15. Howells, M.; Hermann, S.; Welsch, M.; Bazilian, M.; Segerström, R.; Alfstad, T.; Gielen, D.; Rogner, H.; Fischer, G.; Van Velthuisen, H.; et al. Integrated Analysis of Climate Change, Land-Use, Energy and Water Strategies. *Nat. Clim. Change* **2013**, *3*, 621–626. [\[CrossRef\]](#)
16. Endo, A.; Burnett, K.; Orenco, P.; Kumazawa, T.; Wada, C.; Ishii, A.; Tsurita, I.; Taniguchi, M. Methods of the Water-Energy-Food Nexus. *Water* **2015**, *7*, 5806–5830. [\[CrossRef\]](#)
17. Bleischwitz, R.; Spataru, C.; VanDeveer, S.D.; Obersteiner, M.; Van Der Voet, E.; Johnson, C.; Andrews-Speed, P.; Boersma, T.; Hoff, H.; Van Vuuren, D.P. Resource Nexus Perspectives towards the United Nations Sustainable Development Goals. *Nat. Sustain.* **2018**, *1*, 737–743. [\[CrossRef\]](#)

18. Stamou, A.-T.; Rutschmann, P. Optimization of Water Use Based on the Water-Energy-Food Nexus Concept: Application to the Long-Term Development Scenario of the Upper Blue Nile River. *Water Util. J.* **2020**, *25*, 1–13.
19. Drobinski, P.; Rivera Ferre, M.G.; Monem, M.A.; Hatab, A.A.; Behnassi, M.; Chfadi, T.; Cramer, W.; Debolini, M.; Driouech, F.; El-Kenawy, A.; et al. Nexus Approach to Enhance Water-Energy-Food Security and Ecosystems Resilience under Climate Change in the Mediterranean. *npj Clim. Action* **2025**, *4*, 115. [\[CrossRef\]](#)
20. European Commission. *Eurostat Seasonality in the Tourist Accommodation Sector*; European Commission: Brussels, Belgium, 2025.
21. Gössling, S.; Peeters, P.; Hall, C.M.; Ceron, J.-P.; Dubois, G.; Lehmann, L.V.; Scott, D. Tourism and Water Use: Supply, Demand, and Security. An International Review. *Tour. Manag.* **2012**, *33*, 1–15. [\[CrossRef\]](#)
22. Ruggieri, G.; Platania, M. Islands' Tourism Seasonality: A Data Analysis of Mediterranean Islands' Tourism Comparing Seasonality Indicators (2008–2018). *Sustainability* **2024**, *16*, 3674. [\[CrossRef\]](#)
23. Birahim, S.A. Monthly National Water and Carbon Accounting of Desalination-Linked Balance Closure in the Maldives. *Commun. Sustain.* **2026**, *1*, 64. [\[CrossRef\]](#)
24. Teresi, E.; Chiavetta, C.; Freni, G.; Caroscio, L.; Bonoli, A. Renewable Energy Integration in Seawater Desalination: A Life Cycle Costing Perspective for Sustainable Water Supply. *Clean. Environ. Syst.* **2026**, *20*, 100409. [\[CrossRef\]](#)
25. Gao, D.; Chen, A.S.; Memon, F.A. A Systematic Review of Methods for Investigating Climate Change Impacts on Water-Energy-Food Nexus. *Water Resour. Manag.* **2024**, *38*, 1–43. [\[CrossRef\]](#)
26. European Commission. Joint Research Centre. *Water—Energy Nexus in Europe*; European Commission: Brussels, Belgium, 2019.
27. Mitsopoulos, G.; Tzanes, G.; Vakondios, D.; Stamou, A.T.; Stamou, A.I. Climate Change Adaptation of Water Supply Systems in Greek Islands: The Case of Hermoupolis Water Supply System. In Proceedings of the International Symposium & Workshop “Sustainable Solutions at Times of Transition (SUST 2025)”, Nisyros, Greece, 15–17 September 2025.
28. World Health Organization. *Climate Change and Drinking Water Safety*; World Health Organization: Geneva, Switzerland, 2017.
29. Intergovernmental Panel On Climate Change (IPCC). *Climate Change 2022: Impacts, Adaptation and Vulnerability: Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Pörtner, H.-O., Roberts, D.C., Tignor, M., Poloczanska, E.S., Mintenbeck, K., Alegria, A., Craig, M., Langsdorf, S., Löschke, S., Möller, V., et al., Eds.; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2022; ISBN 978-1-009-32584-4.
30. Vousdoukas, M.I.; Mentaschi, L.; Voukouvalas, E.; Verlaan, M.; Feyen, L. Extreme Sea Levels on the Rise along Europe's Coasts. *Earth's Future* **2017**, *5*, 304–323. [\[CrossRef\]](#)
31. Intergovernmental Panel on Climate Change (IPCC). *Climate Change 2021—The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, 1st ed.; Cambridge University Press: Cambridge, UK, 2021; ISBN 978-1-009-15789-6.
32. Lattemann, S.; Höpner, T. Environmental Impact and Impact Assessment of Seawater Desalination. *Desalination* **2008**, *220*, 1–15. [\[CrossRef\]](#)
33. Zhang, X.; Alexander, L.; Hegerl, G.C.; Jones, P.; Tank, A.K.; Peterson, T.C.; Trewin, B.; Zwiers, F.W. Indices for Monitoring Changes in Extremes Based on Daily Temperature and Precipitation Data. *WIREs Clim. Change* **2011**, *2*, 851–870. [\[CrossRef\]](#)
34. World Meteorological Organization. *Guidelines on Analysis of Extremes in a Changing Climate in Support of Informed Decisions for Adaptation*; World Meteorological Organization: Geneva, Switzerland, 2009.
35. Svoboda, M.; Hayes, M.; Wood, D. *Standardized Precipitation Index User Guide*; World Meteorological Organization: Geneva, Switzerland, 2012.
36. Expert Team on Climate Change Detection and Indices (ETCCDI) Indices of CLIMPACT and CLIMDEX. Available online: <https://www.climdex.org/learn/indices/> (accessed on 6 April 2026).
37. European Environment Agency. *Climate Change, Impacts and Vulnerability in Europe 2020: An Indicator-Based Report*; European Environment Agency: Copenhagen, Denmark, 2020.
38. Steadman, R.G. The Assessment of Sultriness. Part I: A Temperature-Humidity Index Based on Human Physiology and Clothing Science. *J. Appl. Meteor.* **1979**, *18*, 861–873. [\[CrossRef\]](#) [\[PubMed\]](#)
39. Garner, G.G.; Hermans, T.; Kopp, R.E.; Slangen, A.B.A.; Edwards, T.L.; Levermann, A.; Nowicki, S.; Palmer, M.D.; Smith, C.; Fox-Kemper, B.; et al. *IPCC AR6 Sea Level Projections 2021*; IPCC: Geneva, Switzerland, 2021.
40. Cotrim, C.; Toimil, A.; Losada, I.; Menéndez, M.; Lobeto, H. Assessing Extreme Total Water Levels across Europe for Large-Scale Coastal Flood Analysis. *Nat. Hazards Earth Syst. Sci.* **2026**, *26*, 1935–1954. [\[CrossRef\]](#)
41. Tsilimigkras, A.; Lazaridis, M.; Voulgarakis, A.; Varotsos, K.V.; Karali, A.; Giannakopoulos, C.; Stamou, A.; Koutroulis, A. Climate Projections for Greece: Defining a Regional Sub-Ensemble from the CMIP6 Landscape. *Theor. Appl. Climatol.* **2026**, *157*, 123. [\[CrossRef\]](#)
42. Varotsos, K.V.; Dandou, A.; Papangelis, G.; Roukounakis, N.; Kitsara, G.; Tombrou, M.; Giannakopoulos, C. Using a New Local High Resolution Daily Gridded Dataset for Attica to Statistically Downscale Climate Projections. *Clim. Dyn.* **2023**, *60*, 2931–2956. [\[CrossRef\]](#)

43. Varotsos, K.V.; Katavoutas, G.; Kitsara, G.; Karali, A.; Lemesios, I.; Patlakas, P.; Hatzaki, M.; Tenentes, V.; Sarantopoulos, A.; Psiloglou, B.; et al. CLIMADAT-GRid: A High-Resolution Daily Gridded Precipitation and Temperature Dataset for Greece. *Earth Syst. Sci. Data* **2025**, *17*, 4455–4477. [[CrossRef](#)]
44. Vousdoukas, M.I.; Mentaschi, L.; Voukouvalas, E.; Bianchi, A.; Dottori, F.; Feyen, L. Climatic and Socioeconomic Controls of Future Coastal Flood Risk in Europe. *Nat. Clim. Change* **2018**, *8*, 776–780. [[CrossRef](#)]
45. Becken, S.; Scott, D. Tourism and Climate Change Stocktake: A Call to Action. *J. Sustain. Tour.* **2024**, *32*, 2018–2038. [[CrossRef](#)]
46. Peeters, P.; Papp, B. Pathway to Zero Emissions in Global Tourism: Opportunities, Challenges, and Implications. *J. Sustain. Tour.* **2024**, *32*, 1784–1810. [[CrossRef](#)]
47. RECREATE Project Syros—South Aegean (GR) Case Study. Available online: <https://recreate4water.eu/case-studies/syros-south-aegean-gr> (accessed on 6 April 2026).
48. Leitner, M.; Dworak, T.; Johnson, K.; Lourenço, T.C.; Lexer, W.; Vanneuville, W.; Tomasova, A.; Prutsch, A. *Using Key Type Measures to Report Climate Adaptation Action in the EEA Member Countries*; European Topic Centre on Climate Change Impacts, Vulnerability and Adaptation (ETC/CCA): Lecce, Italy, 2021.

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