

Review

Challenges and Opportunities for Sustainable Management of Water Resources in the Island of Crete, Greece

V. A. Tzanakakis ^{1,2,*}, A. N. Angelakis ^{3,4} , N. V. Paranychanakis ⁵, Y. G. Dialynas ⁶ and G. Tchobanoglous ⁷ 

¹ Hellenic Agricultural Organization Demeter (HAO-Demeter), Soil and Water Resources Institute, 57001 Thessaloniki, Greece

² Department of Agriculture, School of Agricultural Science, Hellenic Mediterranean University, Iraklion, 71410 Crete, Greece

³ HAO-Demeter, Agricultural Research Institution of Crete, 71300 Iraklion, Greece

⁴ Union of Water Supply and Sewerage Enterprises, 41222 Larissa, Greece; angelak@edeya.gr

⁵ School of Environmental Engineering, Technical University of Crete, 73100 Chania, Greece; niko.paranychanakis@enveng.tuc.gr

⁶ Department of Civil and Environmental Engineering, University of Cyprus, Nicosia 1678, Cyprus; ydialy01@ucy.ac.cy

⁷ Department of Civil and Environmental Engineering, University of Davis, Davis, CA 95616, USA; gtchobanoglous@ucdavis.edu

* Correspondence: vtzanakakis@hmu.gr

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Abstract: Crete, located in the South Mediterranean Sea, is characterized by long coastal areas, varied terrain relief and geology, and great spatial and inter-annual variations in precipitation. Under average meteorological conditions, the island is water-sufficient (969 mm precipitation; theoretical water potential 3284 hm³; and total water use 610 hm³). Agriculture is by far the greatest user of water (78% of total water use), followed by domestic use (21%). Despite the high average water availability, water scarcity events commonly occur, particularly in the eastern-south part of the island, driven by local climatic conditions and seasonal or geographical mismatches between water availability and demand. Other critical issues in water management include the over-exploitation of groundwater, accounting for 93% of the water used in agriculture; low water use efficiencies in the farms; limited use of non-conventional water sources (effluent reuse); lack of modern frameworks of control and monitoring; and inadequate cooperation among stakeholders. These deficiencies impact adversely water use efficiency, deteriorate quality of water resources, increase competition for water and water pricing, and impair agriculture and environment. Moreover, the water-limited areas may display low adaptation potential to climate variability and face increased risks for the human-managed and natural ecosystems. The development of appropriate water governance frameworks that promote the development of integrated water management plans and allow concurrently flexibility to account for local differentiations in social-economic favors is urgently needed to achieve efficient water management and to improve the adaptation to the changing climatic conditions. Specific corrective actions may include use of alternative water sources (e.g., treated effluent and brackish water), implementation of efficient water use practices, re-formation of pricing policy, efficient control and monitoring, and investment in research and innovation to support the above actions. It is necessary to strengthen the links across stakeholders (e.g., farmers, enterprises, corporations, institutes, universities, agencies, and public authorities), along with an effective and updated governance framework to address the critical issues in water management, facilitate knowledge transfer, and promote the efficient use of non-conventional water resources.

Keywords: water resources management; water scarcity; water reuse; climate variability; circular economy; sustainability

1. Prolegomena

The vital role of water in sustaining life on earth was recognized early; Aristotle (384–322 BC) commenting Thales of Miletus (ca. 524–545 BC) declared: “*Besides this (water is the primary principle), another reason for the supposition would be that the semina of all things have a moist nature . . .*” [Metaph. 983 b26–27]. Globally, population expansion and economic growth have increased the demand for adequate, clean, and safe water, challenging existing water resource policies and management, administrative schemes, and infrastructure development [1–3]. This situation is expected to deteriorate in the future, particularly in areas with pre-existing water shortages rendering them particularly vulnerable to climate change [4]; e.g. the Mediterranean basin [5–7]. Agriculture, domestic, and industry sectors are globally the ones with the biggest dependency on water availability and will likely be the most affected by the impact of climate change. New approaches are, thus, needed to ensure sustainable water use, while preserving water resources, environmental quality, and economic development [8–10].

The island of Crete is subjected to significant challenges regarding the management of water resources arising mainly from its location, climate, history, and culture. Crete, located in the South Mediterranean Sea, is characterized by long coastal areas, varied terrain relief, and great spatial and inter-yearly rainfall variations [11]. As a result, the island of Crete is subjected to uneven spatial availability of water resources [12] and variable water imbalances across the island. For instance, the western Crete tends to have a positive water balance, as contrasted to the eastern part which is more vulnerable to water shortages and drought events [13]. Such a water scarcity phenomena are expected to become more frequent in the Mediterranean in the near future and must be seriously considered by decision makers and water management frameworks.

Water management in Crete is primarily governed by the Water Frame Directive (WFD) 2000/60/EC and other relevant EU regulatory provisions supervised by a complex stakeholder network of national, regional, and local agencies [14,15]. Experience so far points to issues in the implementation of the existing policies, while several chronic problems remain to be addressed, further exacerbating the situation. These problems can be summarized as: (a) the labyrinthine legislation, (b) the confusing competences of the public services, (c) the delayed planning at national and regional level, and (d) the lack of modern perception on water management (particularly in the agricultural sector). The lack of a strategy on the use of non-conventional water sources, particularly in agriculture [16], or for aquifer recharge is a characteristic example of the latter.

The European Union (EU) has set a goal to increase water reuse from 1.7 to 6.6 billion m³/year equivalent to 50% of the effluent produced by wastewater treatment plants (WWTPs) that may reduce fresh water use up to 5%. For Greece, it has been estimated that effluent from existing WWTPs can save up to 3.2% of the water used in agriculture [12]. Such a prospect is very promising for the local and regional economy with strong benefits on water resources availability, agricultural production, and development of rural communities [17–20]. However, to date in Crete, despite its high potential for water reuse [15], water recycling is not a common practice, and most of treated wastewater is discharged to the sea. Given the need to respond to intensive water shortages and the challenges imposed by climate variability, it is imperative to identify the causes of the low effluent reuse in order to provide effective solutions within an expanded and improved water management framework.

The main objectives of the present study are to (a) describe the available water resources of Crete; (b) identify barriers, constraints, opportunities, and future challenges in water resources management; and (c) propose solutions and directions for a more sustainable use of water resources, emphasizing the use of non-conventional sources (e.g., desalinated, recycled, and brackish water). For the purposes of this study, information has been compiled on the historical evolution of water management, spatial-temporal

variation of climate, existing water governance framework, water availability considering all the potential sources, and infrastructure (i.e., dams), derived from governmental–private sources and literature, to provide insights in possible deficiencies, gaps, and challenges. Suggestions and possible solutions are presented to help improve water resources management, particularly in areas with water scarcity and to highlight the benefits derived by the proper use of non-conventional water in Crete, Greece, and in other EU countries.

2. Historical Evolution of Water Resources Management in Crete

Archeological evidence has revealed the development of an advanced civilization in Crete and in the islands of south Aegean Sea (Santorini) during the Bronze Age (ca. 3200–1100 BC). During that period, a number of technologies focused on water resources management were developed, including hydrogeology, design and construction of aqueducts and water impounds, water and wastewater mains, runoff management, agricultural irrigation, as well as use of water for recreation purposes [21]. The documented evidence provides support that the Minoan people were aware of the basic principles of water management well before the scientific approach of our times [22]. Their technologies were expanded to the mainland Greece during the dominance of Myceneans (ca. 1600–1100 BC) and later transferred to the Classical and Hellenistic times (ca. 500–67 BC) when they were further improved [23].

During the Roman occupation (ca. 67 BC–330 AD), Crete was characterized by technological innovations in infrastructure development including public buildings, fine mosaics, toilets, sewers, drains, and other hydraulic works, in a number of cities (Gortys, Chersonissos, Ierapytna, Aptera, Lyttos, and Lebena), which were heavily influenced by Hellenic philosophy. Furthermore, large-scale aqueducts and cisterns were constructed (e.g., Gortys' aqueduct and cisterns in Aptera) [24].

From 961 to 1204 AD, technologies for water supply were implemented in big cities of Crete, which was then a part of the Byzantine Empire. Large-scale water projects were also developed and implemented during Venetian governance (ca. 1204–1668 AD) to address water supply and management issues. Indicative are the Morozini's aqueduct, as well as the rainwater harvesting cisterns in Rethymnon and Grambousa [25]. During the Ottoman (ca. 1669–1898 AD) and Egyptian (ca. 1830–1840 AD) eras, and until the beginning of 20th century, all of water infrastructure developed by Romans and Venetians was maintained and kept in operation [26]. In the 20th century, new modern water technologies were introduced and applied, such as the development of deep wells, pumps, pipes, etc.

Collectively, the water management and engineering in the island of Crete passed through a number of different stages but maintained a characteristic continuity over the centuries and even through the Dark Ages. Bridges from the past to the future are still present, albeit oftentimes, they are invisible to those who cross them, including ancient constructions that have been in operation continuously or intermittently to this day. The survival of different types of cisterns developed in Minoan and Mycenaean times, which are still in operation in many anhydrous Aegean islands [27], is another example. These constructions constituted the basis for their later development into the modern technological age [28].

Current-day engineers typically use a design period for hydro-structures operation of about 40 to 50 years, which is related to economic considerations. However, it is notable that several ancient Cretan hydraulic works have been operating efficiently for millennia, in some cases until the contemporary times, e.g., sewerage and drainage systems [29]. A. Mosso (1910), an Italian writer who visited the area in the early 20th century, during a heavy rain, noticed that the drains/sewers functioned perfectly and recorded the incident saying *"I doubt if there is other case of stormwater drainage system that works 4000 years after its construction"* [30]. Additionally, the American H. F. Gray (1940), reported that *"you can enable us to doubt whether the modern sewerage and drainage systems will operate at even a thousand years"* [31].

3. The Physical Setting Demographics, Activities and Land Use

3.1. Location Morphology Population and Economic Activities

The island of Crete is located in southern Europe, bordering the Aegean Sea, Ionian Sea, and the Mediterranean Sea (Figure 1). Crete has an elongated shape, of about 260 km from west to east and at its widest 60 km and a coastline of 1046 km long. To the south, Crete is bordered by the Libyan Sea, to the west the Myrtoon Sea, to the east the Karpation Sea and to the north the Sea of Crete. The geographical position of Crete between three continents has influenced its historical course throughout antiquity and modern times [32].



Figure 1. The location of Crete (Google earth, 2019).

The total area of Crete is 8336 km², accounting for the 6.36% of the total area of Greece, and is divided into four prefectures, from west to east: Chania (2342 km²), Rethymnon (1487 km²), Iraklion (2626 km²), and Lasithi (1810 km²). The main mountains running from west to east include the White Mountains (2453 m), the Idis (Pseiloritis) (2456 m) and Asterousian (1280 m) mountains in the central Crete, and the Dikti mountain (2148 m) in the east. Based on its geomorphology, Crete consists of three basic zones: the zone with an altitude of >400 m (mountainous zone), the intermediate zone (200–400 m), and the low zone (<200 m). The mountainous and the intermediate zones occupy approximately 77.3% of Crete's area and extend from the western to the eastern part of the island with some interruptions by valleys and gorges. The island of Crete is considered an independent river basin district (RBD) [14].

The permanent population of Crete is 623,065 following an almost linear increase over the last century until it leveled off in 2011 [33]. It represents 5.76% of the population of Greece [34,35]. The population has since followed a decreasing trend (Figure 2). Based on the total area and the number of inhabitants, the population density in Crete is estimated to 81.93 inh./km², which is close to the country average (82.90 inh./km²). This number, however, increases significantly in the summer period due to large number of visitors.

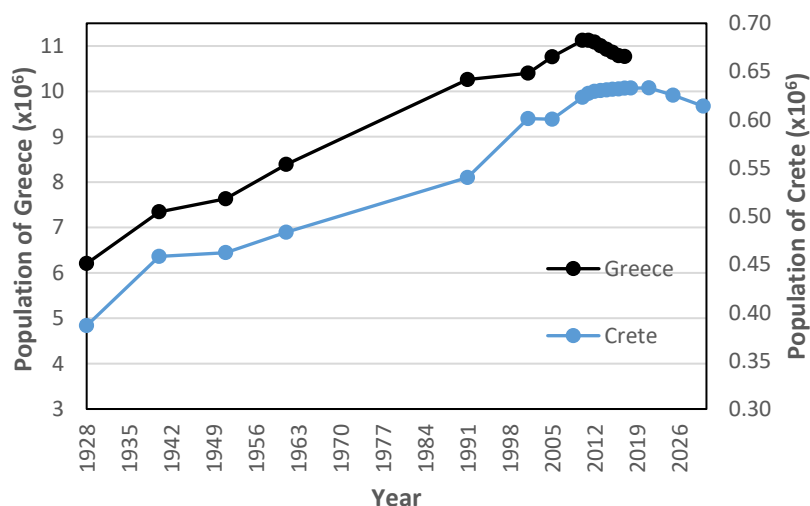


Figure 2. Evolution of the populations of Greece and Crete [33].

In economic terms, Crete produces 4.9% (13,000 M€) of total GNP of the Greece. The critical pillar of the Cretan economy is tourism, based on the accommodation of numerous tourists attracted by Cretan culture, landscapes, and climate as well as by the several archaeological sites throughout the island. The overnight stays per year in Crete are estimated to be about 16,449,065 [36]. There are also 55 Natura 2000 regions in Crete. The agricultural sector is another critical pillar of the Cretan economy based mainly on the production of wine, olive oil, and vegetables. Dairy products also have an important contribution to the Cretan economy.

3.2. Geology and Hydrogeology

Geology exerts considerable influence on surface and subsurface water flow in Crete [37]. The island's geology includes four pre-Neogene major nappes and one autochthonous isotopic zone. The nappes were transported from the north along eastern–western (E-W) trending thrusts and were placed between Late Eocene and Early Miocene times. Shortly after nappe emplacement during the Middle/late Miocene a northern–southern (N-S) directed extensional regime was established in the region, due to the relative plate behavior and the resultant geodynamic condition at the European margin, where the first E-W trending basins were formed [38,39], followed by two main faults generation: (a) in the late Messinian, an arc-parallel extension formed the N-S trending and smaller basins, and (b) in middle Pliocene, a fault development resumed in two normal directions NW-SE and NE-SW [40]. This period was associated with the deposition within the graben of Miocene to Quaternary sediments, which consist mainly of red beds, sandstones, marls, limestones, and evaporites, with overlying depositions of red lacustrine conglomerates and recent alluvium sediments [41].

The hydro-geologic structure of Crete is a result of the nappe emplacement and post emplacement tectonic and depositional history [38]. Shallow aquifers are hosted by the Neogene–Quaternary sediment filled grabens whereas deeper karstic aquifers flow through the carbonates of the pre Neogene nappes [39]. Underground and spring water move through the fault systems, which impede or facilitate the flow depending on structural positions. Major faults with general N-S orientation enable preferential water flow, while faults W-E oriented may act as impermeable boundaries [37]. Approximately 80% of the ground water resources of the island are associated with deep karstic aquifers whereas the remaining is attributed to the Neogene–Quaternary aquifers [39]. In the area of Crete, there are 47 gauged springs divided into freshwater, brackish, and undersea springs [42,43]. Most of springs belong to the karst hydrogeological system (Lefka Ori, Idi, Dikti, and Sitia) discharging around 500 hm³/year. Brackish springs located at coastal areas have the greater flows, such as Almyros in Iraklion that discharges around 250 hm³/year while spring in Agios Nikolaos discharge 82 hm³/year. There are also submarine discharges spread in coastal area of Crete [43]. The geological structure and

geomorphology of Crete create many small hydrologic basins (Figure 3). The greater hydrologic basins are these of Anapodiaris (600 km²) and Geropotamos (525 km²) found in Messara-Valey (Figure 3).

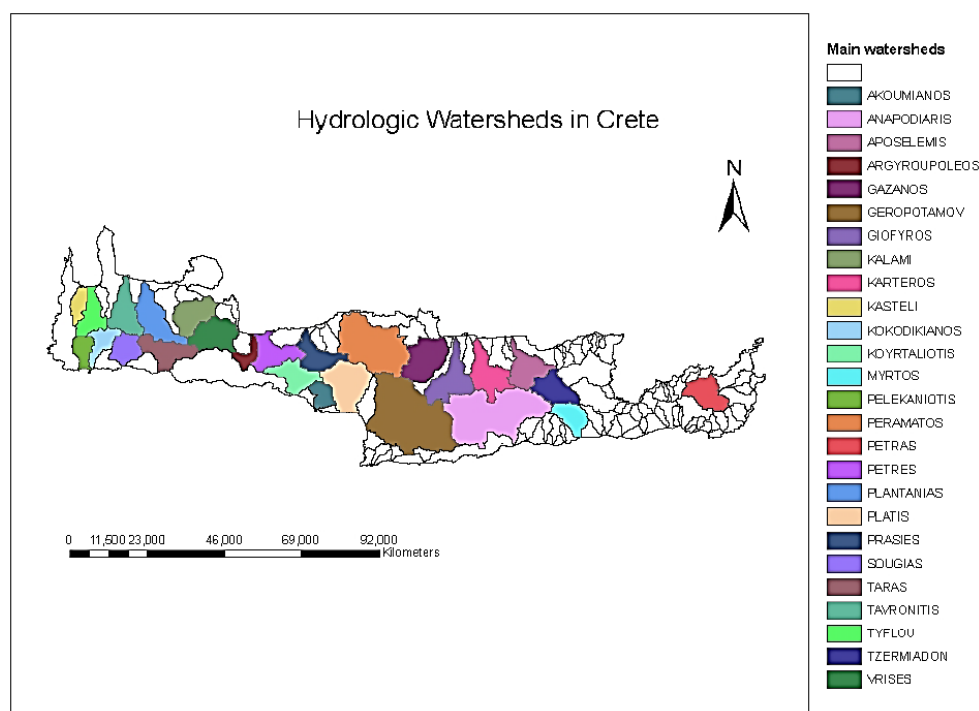


Figure 3. The most important hydrologic basins of Crete (modified from [43]).

3.3. Climate

History. In contrast to earlier ancient civilizations (Egypt, Mesopotamia, Indus) that flourished in water-abundant environments (large river valleys), ancient Greeks and especially Cretans preferred to establish their settlements in dry, water-scarce sites. Thus, all major ancient Cretan cities, during the several phases of the Cretan civilizations, were established in areas that had low water availability. Another characteristic is that, despite the existence of some small-scale rivers and lakes in Crete, no major city has been built close to these resources. It can be argued that climate and health could have been the main criteria, as dry climates are considered healthier and protect the population from water-borne diseases. It is worth noting that the progress in Cretan civilizations over the centuries has been connected closely to hygienic living standards and a comfortable lifestyle. To achieve these, both technological infrastructure and management solutions were developed.

Previous studies on climate variations in the Mediterranean region during the Holocene period have documented the occurrence of distinct climatic periods during the past 5000 years (e.g., cold period, ca. 4500–3000; cold and humid period, ca. 3000–2200; and a warm period, ca. 2200–1400 BC) [44]. Despite the varying climatic conditions during the past 5000 years, it seems that the overall abundance of water resources was never the case for important Cretan cities such as Knossos, Zakros, Phaistos, Kissamos, and Gortys. To address the (occasional) water scarcity in specific areas, ancient Cretans developed innovative technological means to capture, store, and convey water even from long distances [26]. Thus, the main technical and hydraulic innovations were associated with the management of water resources, followed by sewerage and drainage systems, including urinals and toilets, bathrooms with tubs, laundry slabs and basins, as well as by effluent disposal sites. Such operations have been practiced in varying forms since ca. 3000 BC [44].

Tsonis et al. (2010) indicate that wetter conditions during the middle Holocene were followed by drier conditions and that around 1450 BC a long stretch of drier conditions commenced ending around 1200 BC. The authors also presented a synthesis of historical, climatic, and geologic evidence

to support the hypothesis that climate, instigated by an intense El Nino activity, contributed to the demise and eventual disappearance of the Minoan civilization. Thereafter, during the Iron period (ca. 1300–600 BC), another cold and humid period prevailed. During classical and Hellenistic times (ca. 600–67 BC), the climate was rather warm and dry. During the Roman period (ca. 67 BC–330 AD), a short colder and more humid period prevailed. Finally, a warm and dry climate prevailed during the Arab period with a peak of high temperatures and drought ca. 800–1000 AD [21]. Taken together, the climatic and hydrologic conditions in Crete have been characterized by high spatial and temporal variability (Figure 4) throughout the long history of the island [32].

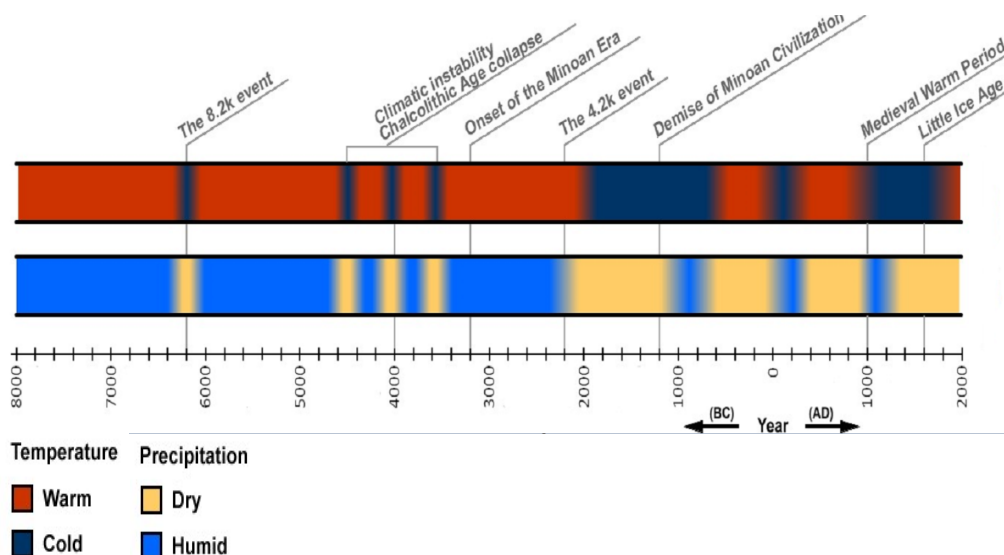


Figure 4. Climate reconstruction of Crete for the last 10,000 years based on proxy and historical data (with permission of [32]).

Today, Crete falls within two major climatic zones, the Mediterranean and the North African zone. As a result, the climate is primarily temperate with relatively high atmospheric humidity and quite mild summer and winters. The average temperature in the summer varies between 15 and 30 °C, with the maximum values up to or exceeding 40 °C. More sunny days and higher temperatures prevail across the south coast, including the Messara valley and Asterousia mountains, driven mainly by the prevailing North African climatic zone [45].

Precipitation. The precipitation in Crete is characterized by spatial and temporal variation increasing towards the western and north parts of the island [11]. The mean annual precipitation in the eastern part has been estimated at 675 mm/year, while in western Crete at 1179 mm/year, with an overall average of 967 mm/year (Table 1). The spatial distribution of mean annual precipitation [39] correlates well with altitude, due to orographic effects [46]. The calculated mean lapse rate is 61 mm/100 m in altitude (range: 25 to 100 mm). Indicative of the precipitation variation along Crete, is the 440 mm/year at the valley of Ierapetra (SE Crete) and the 2000 mm/year at the Askifou upland (NW Crete).

Hydrologic years in Crete are clearly distinguished in wet and dry seasons, with the wet season lasting from October to March and the dry season lasting from April to September. In the prefecture of Iraklion, on average, the 87% of precipitation occurs during the wet period. The average number of rainy days ranges from 15 in December and January to almost null in July and August. Extreme daily precipitation events of 107 mm in Iraklion and 250 mm in Chania (two events on February 2019) have been recorded that exert a strong effect on maximum annual stream flows [49]. The seasonal stability of precipitation pattern in Iraklion, which exhibits a relatively stable wet/dry pattern for more than a century (1909 to 2018), is demonstrated in Figure 5b. Over the past 30 years, the intensity and frequency of daily precipitation maxima have declined slightly according to the time series (Figure 5c),

yet precipitation extremes could potentially intensify in the future (see Section 4.1). In Chania, average precipitation is higher than that of Iraklion, but it follows a similar trend over the last century (Figure 5a).

Table 1. Average annual estimations of the hydrologic cycle components in Crete on normal, wet, and dry years. Source: [14].

Hydrologic Conditions	Unit	Precipitation	Actual ET (57.50%)	Run-off (15.00%)	Infiltration (27.50%)
Normal year	mm	967			
	hm ³	7727.47	4443.30	1159.12	2125.05
Wet year	mm	1244			
	hm ³	10,369.98	5962.74	1555.50	2851.74
Dry year	mm	610			
	hm ³	5084.96	2923.85	762.75	1398.36
Year 2017–2018	mm	480			
	hm ³	4001.28	2300.74	600.19	1100.35

Data of 40 years from 90 Meteorological stations.

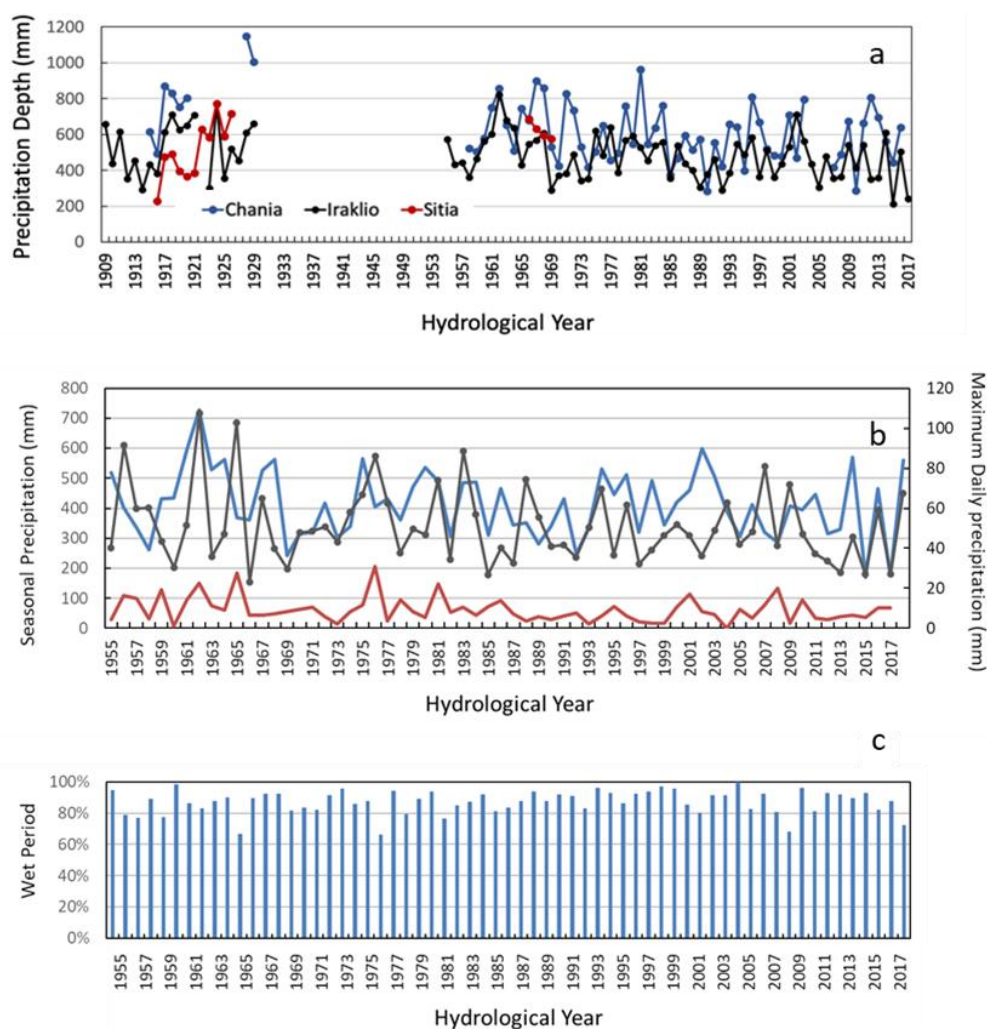


Figure 5. Precipitation in Chania, Iraklion, and Sitia from 1909 to 2017 (a). Precipitation in the prefecture of Iraklion, Crete, during the wet (blue line) and dry seasons (red line) (b). Maximum daily precipitation is given in black line (left y-axis) (b). Blue bars (c) above illustrate the wet season precipitation as a percentage of annual rainfall height (data available by the National Oceanic and Atmospheric Administration. Sources: [32,47,48].

Air temperature. The mean annual temperature ranges from 17 to 20 °C. Air temperature increases from West (16.96 °C Alikianos station) to east (18.33 °C Siteia station) and decreases from south (19.55 °C Ierapetra station) to north (18.55 °C Siteia station).

Humidity. The driest months of the year are June and July (mean relative humidity 48.9% in Souda and 59.9% in Iraklion). The most humid month is December (72% in Souda and Siteia and 67% in Iraklion).

Potential evapotranspiration. Potential evapotranspiration (ET_o), estimated with Penman–Monteith method, varies from 1240 to 1570 mm/year. The intra-annual monthly ET ranges from about 25 mm (winter) to 225 mm (summer). The annual actual ET accounts from 75% to 85% of the annual precipitation in low elevation areas (< 300 m abs) and 50% to 70% in high elevation areas.

Hydrological water balance. The estimated hydrological water balance of Crete for three hydrological conditions, namely a normal year with a return period equal to or exceeding 50%, a wet year with a return period equal to or exceeding 10% and a dry year with a return period equal to or exceeding 90% is shown in Table 1. Estimations were derived from the analysis of a 40-year time series and on surface models of major catchments and ground water models of aquifers [14].

3.4. Land Use

Land use and habitat characterization has been studied extensively [50] as a tool of guidance for regional planning and policy. An overview of categorized land uses, including cropland, drylands, forests, mountains, and urban areas is given in Figure 6. According to the latest water management plan of Crete [15], forests/semi-natural areas and agricultural land account for 55.56% and 42.38% of the total area, respectively. The distribution of the different land uses across the three drainage basins of Crete (north (EL1339), south (EL1340), and east (EL1341) parts) are summarized in Table 2.

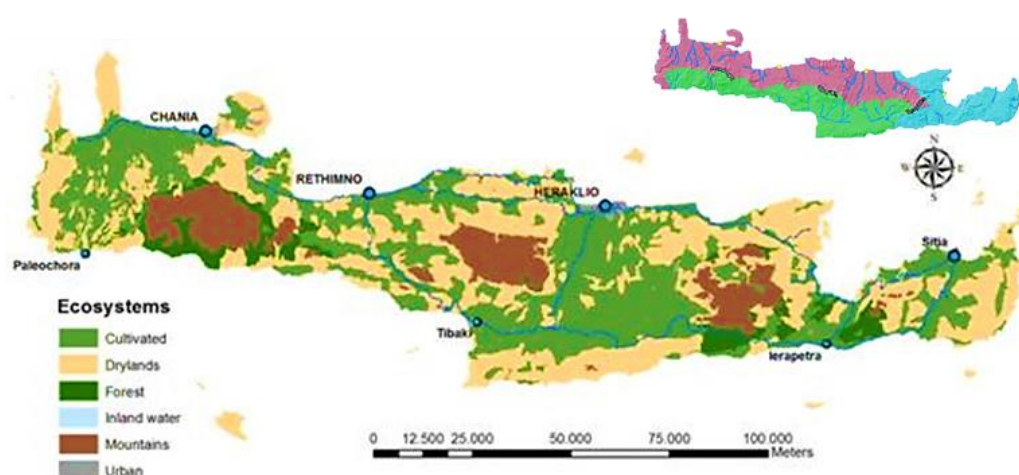


Figure 6. Ecosystems in Crete (modified from [51]). Small figure illustrates the three drainage basins of Crete (north (EL1339) (purple), south (EL1340) (green), and east (EL1341) (blue) (modified from [15]).

Table 2. Drainage basin coverage of Crete by different land uses. Source: [15]).

Drainage Basin	Agriculture (%)	Forest and Semi-Natural Areas (%)	Artificial Areas (%)	Water Lands (%)
EL1339	45.65	51.06	3.22	0.07
EL1340	42.54	56.90	0.50	0.05
EL1341	35.68	62.51	1.76	0.05
Average	42.38	55.59	1.98	0.06

4. Water Management

Sustainable water management is a challenge for Cretan regional authorities to meet water requirements driven by different economic activities (agricultural, domestic, livestock, and industrial use) and to preserve the water resources of the island. Sustainability is not a straightforward task considering the complexity of the existing legislative framework involving several stakeholders from multidisciplinary sectors. Given the instability in the current economic environment and the challenges arising from and the need for adaption to climate variability, sustainability becomes even more challenging. In this context, available administrative structure and legislative framework, spatial and temporal variations water resources availability, and challenges in water management are presented and interpreted to identify critical topics, options, and alternatives.

4.1. Administrative Structure and Principal Legislation

In Crete, water resources management is covered by the 3199/2003 law and the 5/2007 presidential decree, established to achieve synchronization with 200/60/EC WFD of the EU [52]. That Directive, among others, settled for each of the 14 river basin districts (RBD) of Greece (Crete represents the 13th RBD) water management plans, as way to address critical issues and challenges in current and future water management planning. For Crete, the first water management plan was released in 2015 [14]; the first revision of the plan was presented in 2017 [15], covering the period of 2016 to 2021. In the latter, the administrative structure and the responsible authorities in water resources management in Crete are identified and described, including the National Water Committee, National Water Council, and General Secretariat for Water and Environment, at national level, and the Regional Water Council of the Decentralized Administration of Crete, Electoral Region of Crete, and Municipalities [15]. The Decentralized Administration is responsible for the development of national strategic planning (water protection measures), while the Electoral Region and Municipalities are responsible for its implementation. Furthermore, Electoral Region and Municipalities are responsible for the monitoring and control of water resources (level and quality of the ground and surface water) as well as for execution of projects related to water resources exploitation [15].

Besides the WFD, EU via the new EU CAP 2014–20 and other supporting EU directions and measures, such as circular economy concept [53] and measures to mitigate climate change [54], provides a comprehensive institutional umbrella on issues related to water management across the member states to tackle water scarcity in sensitive areas, mitigate climate change impacts, ensure necessary adaptations, and protect water resources. Reuse of treated effluent is among the actions that have been considered and promoted by EU being fully compatible with other (e.g., circular economy and climatic change) policies as aforementioned. To support its policies, the EU provides a variety of financial tools to strengthen knowledge in critical water management issues and to enhance networking and dissemination of knowledge across stakeholders.

4.2. Water Availability and Climate Variability Impacts

The average yearly precipitation on Crete (969 mm) corresponds to approximately 6109 hm³ [55] (Table 3). However, less than 36% of the precipitation is stored in the soil or percolates to deeper horizons. By contrast, ET and runoff to the sea account for 73% and 19% of the precipitation, respectively. As a result, the theoretical total water reserves are estimated to be 3284.17 hm³/year (Table 3), accounting for 54% of precipitation, without considering the potential contribution of non-conventional water recourses.

Table 3. General hydrological data (annual average values of a normal year) for the river basin districts (RBDs) of the island of Crete.

Parameter	Unit	RBD of Crete
Area	km ²	8315.00
Precipitation	mm	969.00
Volume of precipitation	hm ³	6109.00
Evapotranspiration	hm ³	4443.30
Percolation	hm ³	2172.31
Surface runoff	hm ³	1159.12
Theoretical water potential	hm ³	3284.17

Although precipitation theoretically satisfies water requirements (consumption accounts for the 7% of the total precipitation) [12,56], water imbalances have been experienced across the island. These imbalances have been driven by temporal and spatial variations in precipitation, terrain characteristics, vegetation distribution, urban water needs, distribution of water infrastructure (e.g., artificial lagoons and dams), local economy potential and seasonal water demands, and water transportation constraints [12].

Due to its geographical location, the island of Crete is subjected to great vulnerability to climatic conditions [5,56,57]. This vulnerability will become more challenging in the upcoming years due to climate variability [6,57,58], impacting further water availability [56,59] and likely crop productivity [60,61]. Among climatic extremes, in Crete, intense precipitation events, increased frequency of flooding, longer and more intense droughts have been projected [56,57,62]. However, the validity of climate change projections is still under investigation due to assumed initial conditions and assumptions and methodological constraints related to the downscaling of the climatic projections [63,64].

4.3. Water Uses and Critical Topics

The major water uses in Crete are irrigation and domestic use, with relatively small volumes of water used for livestock, landscape irrigation, and industrial applications (Table 4). Agriculture relies on the groundwater (about 93%), whereas domestic and livestock use are equally dependent on surface and subsurface water (Table 4).

Table 4. Withdrawals from surface and underground waters and overall water use in Crete. Source: [15].

Source	Water Uses in 2016 (hm ³ /Year)				
	Domestic	Agriculture	Livestock	Industry	Total
Surface water	39.40 (30.87%)	34.60 (7.23%)	2.10 (50.48%)	0.27 (36.00%)	76.37
Sub-surface water	88.21 (69.10%)	443.81 (92.77%)	2.08 (50.00%)	0.48 (64.00%)	534.58
Total	127.65	478.39	4.16	0.75	610.94
Consumption index (%)	20.89	78.30	0.68	0.12	NA

Domestic applications. Domestic use has been estimated to 127.65 hm³/year (Table 4) driven by permanent population and tourism. Water consumption follows a seasonal pattern with the highest water demands in the summer period due to tourism and the lowest ones in winter. Currently, non-revenue water (NRW) may be the major problem in managing potable water in Greece and especially in Crete. The actual amount of NRW is one of the highest among the EU countries; in some cases, it exceeds 60% of the potable water due to losses in the networks, illegal connections, and non-payments from no-payers/consumers. Mitigation of NRW must be considered in collaboration of water companies with the private sector, under transparent, clean, and controlled processes.

Agricultural Use. In Crete, 87,040 recorded land holdings exist, consisting of mixed (agricultural and livestock), agricultural, and livestock farms, which occupy an area of 364,095 ha (Table 5). Cultivated land occupies 280,075 ha, of which 151,550 ha (about 54%) is irrigated (Table 6). Tree crops (mostly olive trees) dominate agricultural land covering 203,946 ha, of which 119,216 ha (about 58%)

are irrigated. Vineyards occupy 18,962 ha, of which 72% (13,590 ha) are irrigated. Overall, based on records from the Hellenic Statistical Agency [65], the irrigated area has been increasing since 1995 (Figure 7). It has been estimated that water from public irrigation networks is utilized for about 30,300 ha; the rest are irrigated with private water systems. It is worth noting that most of the water used for irrigation is derived from groundwater (Table 4). The irrigation efficiency has been estimated at about 80% [66], due to the wide use of drip or micro-sprinkler irrigation systems.

Table 5. Holdings and areas in mixed, agricultural, and livestock areas of Crete. Source: [65].

Holdings/Areas	Total		Mixed		Agricultural		Livestock	
	Hold-ings	Area (ha)	Hold-ings	Area (ha)	Hold-ings	Area (ha)	Hold-ings	Area (ha)
Region of Crete	87,040	364,096	14,590	225,867	71,619	125,197	831	13,032
Iraklion	41,162	144,098	4787	70,068	36,184	70,348	191	3682
Lasithi	12,981	41,063	1168	19,903	11,729	19,507	84	1653
Rethimnon	13,024	93,703	4517	76,238	8131	14,133	376	3332
Chania	19,873	85,232	4118	59,658	15,575	21,209	180	4366

Table 6. Total and irrigated agricultural areas of Crete. Source: [65].

	Total (Incl. Fallow Land)	Crops on Arable Land	Garden Area	Vineyards	Tree Crops	Fallow Land
Total area (ha)						
Region of Crete	280,075	20,774	6965	18,962	203,946	29,427
Iraklion	129,046	10,173	2814	15,012	90,588	10,459
Lasithi	52,517	3008	1953	1459	36,043	10,054
Rethimnon	41,956	4377	609	934	29,348	6688
Chania	56,556	3217	1590	1558	47,966	2226
Irrigated area (ha)						
Region of Crete	151,550	11,550	7195	13,590	119,216	
Iraklion	87,643	6821	3090	12,519	65,212	
Lasithi	24,731	1851	1915	567	20,398	
Rethimnon	8761	374	594	85	7708	
Chania	30,416	2504	1596	419	25,898	

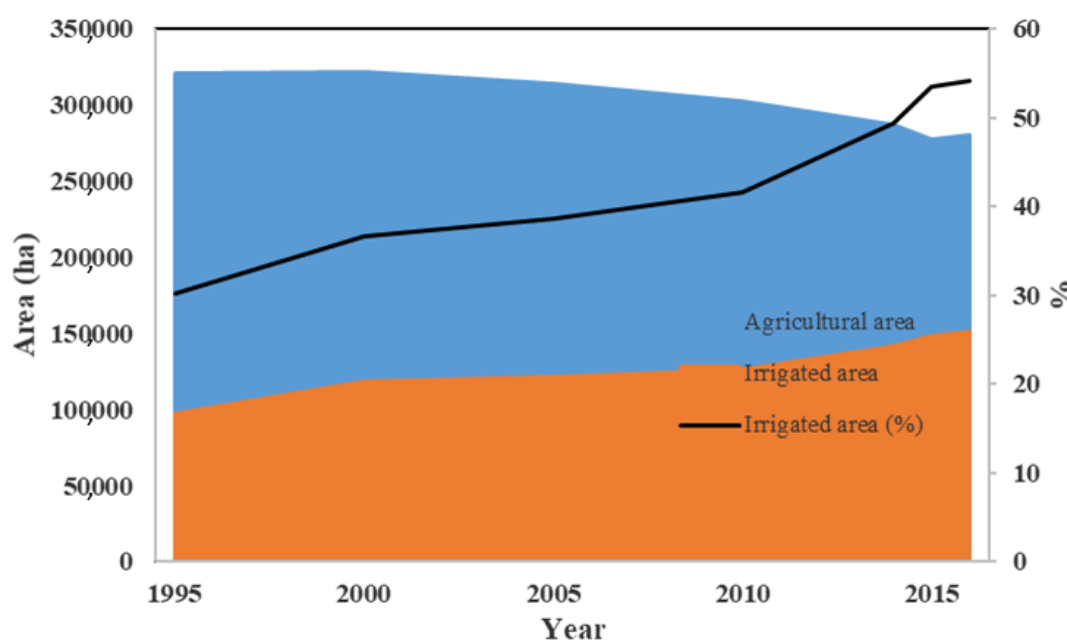


Figure 7. Change of the irrigated area from 1995 until the present (modified from [65]).

Agriculture is by far the greater consumer of water on the island (Table 4) exerting significant pressure on water resources, especially on subterranean water [67–69]. Over-pumping of groundwater

to support agricultural production has led to significant depletion of the aquifers, a problem that is being exacerbated over time, mainly in areas of the southern (e.g., valley of Messara) and eastern part of the island [15,69–71]. These areas are characterized by low precipitation and high temperatures and are highly vulnerable to climate variability. These areas are also subject to other serious risks, such as sea intrusion, soil degradation, and desertification [72–74]. To address the problem of groundwater overexploitation, specific strategies and measures should be applied enhancing primarily water availability in the area by using other water sources as well as measures to improve water use efficiency or availability (transportation, dams) [75,76]. For instance, adoption of appropriate field practices, such as deficit irrigation, new irrigation technologies, use of tolerant to water deficits crops, and/or more water efficient crops, will result in significant water savings eliminating concurrently the adverse effects on crop performance [77,78]. Furthermore, measures that improve monitoring and control of water from the source to farms, along with provision of disincentives (high pricing) for those with high water consumption, will contribute to the efficient use of water. According to recent records, water price in Crete varies greatly across or even within the catchment area, depending on responsible agency, between 0.05–0.65 €/m³ [13,79,80]. Finally, measures that promote knowledge transfer and capacity building across stakeholders may enhance farmers' ability to apply sustainable practices and increase public awareness. Both pricing and non-pricing measures have been supported by the legislative basis of the EU for water management.

Water demand for stock raising and industrial applications. The water demand for stock raising is relatively low but not negligible. The bulk volume of water is used for raising free range stock (sheep and goats) and is estimated to be 4.16 hm³/year (Table 4) [15]. Industrial activities on Crete are limited. The main water consuming industries are wineries and olive oil mills, which are scattered throughout the island. The annual quantities of water used by the industrial sector is estimated to be 0.75 hm³/year (Table 4).

Total water demand. The total annual water needs for Crete are estimated to be about 610.94 hm³/year (Table 4) [15], which correspond to approximately 7.91% of the annual precipitation and to 18.60% of the annual theoretical water potential. Based on these data, it can be inferred that Crete is characterized by high availability of water reserves that may be utilized within an optimized water management plan.

4.4. Conventional Water Resources

4.4.1. Surface

Surface aquatic bodies on the island of Crete include 128 rivers, 1 lake, and 29 transitional and coastal systems distributed throughout Crete. Aquatic bodies also include artificial lagoons and reservoirs (dams). Most of these dams have been built since 1990 onwards and are located all over the area of Crete with a total volume of 280 hm³ (Table 7). Large-scale dams (e.g., the Valsamiotis dam in Chania) are designed to meet existing demands, while others are designed to meet existing and/or future water demands, such as dams of Roumatianos and Derianos in Chania, dam of Plakiotissa in Iraklion, and dam of Amari in Rethymnon [56]. Moreover, the potential of some of the dams, mainly those in the eastern part of the island (e.g., Aposelemis dam) to meet the design expectations, is challenged by the prevalence of consecutive dry years or by shifts in precipitation patterns arising from climate variability [56,81]. The surface aquatic systems of Crete are assessed in the latest river basin water management plan [15] that focuses mainly on the anthropogenic activity induced impacts and on the compatibility with EU 2000/60 Directive criteria. Most of the surface water bodies are classified at the category “is not at risk” (40%) or “probably not at risk” (56%) [15].

Table 7. Major dams in Crete. Source: [14,46,82,83].

Name	Location	Period of Contraction	Type	Total Volume (hm ³)	Usable Volume (hm ³)	Comments
Regular dams						
Potamon	Amari, Rethymnon	1995–2003–2008	Earth dam	22.50	17.50	Water supply and irrigation
Aposelemis	Avdou, Iraklion	2006–2012	Earth dam	25.27	24.36	Irrigation
Valsamiotis	Vatolakos, Chania	2005–2014	RCC ^a (FSHD)	6.00	5.90	Irrigation
Faneromeni	Western Messara	2005	Earth dam	19.67		Irrigation
Mpramianon	Ierapetra	1986	Earth dam	16.00		Irrigation
Ini	Iraklion	2002	Earth dam	1.75		Irrigation
Damanion	Iraklion	2003	Earth dam	1.50		Irrigation
Amourgeles	Iraklion	2004		1.56		Irrigation
Plakiotisas	Iraklion		Earth dam	18.60		Irrigation/ Under construction
Chalavrianou	Iraklion	2018	Earth dam	1.20		Irrigation and Water supply
Partiron	Iraklion	2000	Earth dam	1.50		Irrigation
Armanogion	Iraklion	2004	Earth dam	1.50		Irrigation
Agias	Chania	1929	Earth dam	0.13		Energy, Water supply and Irrigation
Gerakari	Rethymnon		Earth dam	1.75	1.45	Irrigation
		Under planning (Major)				
Plati Potamou	Agia Galini, Rethymnon			51.00		Irrigation
System of 3-dams	Chania			45.00		Irrigation
Dematiou	Iraklio			30.00		Irrigation
Agiou Ioanni	Lasiyhi			18.50		Irrigation
Lithinon	Lasithi			9.00		Irrigation
Small dams (limnodelsamenes)						
Vizariou	Rethimnon	1994		0.66		Irrigation
Agiou Georgiou	Lasithi plateau	2008–2012		2.15		Irrigation
Chavga	Lasithi plateau	1995		0.86		Irrigation
Karavado	Iraklion	1996		0.11		Irrigation
Agion Theodoron	Chania	1998		0.65		Irrigation
Anogion	Rethymnon	2001		0.75		Irrigation and Water supply
Gergeri	Iraklion	2001		0.26		Irrigation
Chrisoskalitisa	Chania	2005		0.56		Irrigation
Arkadiou	Rethymnon	2006		0.60		Irrigation
Thraspanou	Iraklion	2006		0.21		Irrigation
Kountouras	Chania	2008		0.65		Irrigation
Skinia	Iraklion	1997		0.38		Irrigation
Elous	Chania			0.35		Irrigation/ Under construction
Omalou	Chania			0.50		Irrigation/ Under construction
Zou	Lasithi			0.30		Irrigation/ Under construction

^a Roller-Compacted Concrete.

Thermal springs. Out of about 750 recorded thermal springs in Greece, almost 100 are found in Crete [84]. Thermal springs were known in Crete since Classical times when most of them were associated with *Asclepieia* (ancient hospital, e.g., *Asclepieia* in Levina and in Lissos in Crete [85]). There are indications that the water spring in the *Asclepieion* of Levina was saline and was thought to have healing properties. The spring water of Levina, at a temperature of 22 °C, continued to be used for healing purposes during the Historical and Byzantine times [86]. Moreover, analyzed water samples taken from the spring in ancient Lissos in Crete, during the hot season, were found to be in the hypothermic range from 20.3 to 20.7 °C, among the hot and cold seasons, respectively [86]. The spring water, based on chemical analyses, was dominated by a calcium-magnesium-oxycarbonate (Ca-Mg-HCO₃) mineral complex in both periods of time.

4.4.2. Groundwater

The annual underground water supply in Crete is estimated to be $2172.31 \times 10^6 \text{ m}^3/\text{year}$ (Table 8) of which a significant portion is brackish. It is estimated that the total underwater discharges including brackish water amounts to $800\text{--}1000 \times 10^6 \text{ m}^3/\text{year}$. Water potential of the major hydrogeological units of Crete are presented in Table 8 [14,15].

Table 8. Water potential of major hydrogeological units of Crete (table data are based on estimates of over 91 individual hydrogeological units throughout Crete). Source: [14,15].

Hydrogeological Formations	Area (km ²)	Average Annual Precipitation (mm)	Volume of Precipitation (hm ³ /Year)	Average Percolation (%)	Volume of Percolated Water (hm ³ /Year)
Karstic	3333.07	1300	3549	42.55	1510.24
Neogenic	2950.92	693	1799	27.00	485.66
Others	2031.81	780	761	23.18	176.41
Total/Average	8315.80	969	6109	35.56	2,172.31

The intensive exploitation of groundwater, particularly by agricultural activity over the last 50 years, has led to a continual decline in groundwater level, while several coastal aquifers suffer from seawater intrusion [87]. In addition, the water quality of some aquifers has been degraded due to pollution from agricultural, industrial, and touristic activities. In a recent investigation of 91 aquifers, it was found that nine systems (eight in Iraklion and one in Ierapetra-Sitia) had significant or moderate degradation due to elevated salinity and high NO_3^- and SO_4^{2-} concentrations [15]. Moreover, by applying a new groundwater footprint methodology, one aquifer system in Chania, five in Iraklion, and eleven in Sitia also exhibited elevated rates of deterioration [88]. In Crete, 94 municipal WWTPs, 1549 hotels, and 721 industrial units operate, of which 492 are olive mills and 35 dairies. There are also 25 wineries and 23 cement industries [15]. These units constitute potential sources of pollution through the diffusion of the specific organic and inorganic pollutants to ground and surface water. In total, the surface loadings derived from the point, non-point, and other anthropogenic pressures have been estimated to be 34,291.58 ton/year for BOD, 22,010.91 ton/year for N, and 5347.57 ton/year for P [15].

4.5. Potential for the Use of Non-Conventional Water Sources

Non-conventional sources of water must comply with the principles for sustainable development and should be considered in an integrated water resources management plan [89]. These sources mainly comprise recycled, brackish, and desalinated water. Stormwater and wastewater management are also considered.

4.5.1. Stormwater and Wastewater Management

Stormwater management. Cretan coastal system is characterized by a strong seasonal variability, being typically oligotrophic during the dry summer periods with nutrients delivered primarily during the wet winter periods via pulses associated with high rainfall events [90]. These events are the most important drivers of coastal primary production leading to deterioration of water quality especially near densely populated areas. In Crete, stormwater is dispersed to natural recipients, e.g., land, rivers, and transitional and coastal waters [91]. As all major cities of the island are located in coastal areas, storm-water dispersal directly to the sea is the common practice. Bathing water quality parameters are monitored regularly in accordance with the provisions of Directive 2006/7/EC [92]. Furthermore, the ecological and chemical status of coastal waters in Crete is assessed seasonally in accordance with the Water Framework Directive 2000/60/EC [93]. In the past years, based on the results from both monitoring programs, the water quality and status of the coastal waters around Crete was very good [94]. Additionally, the contribution of the wastewater treatment to the bathing water quality, especially in coastal urban areas, is significant.

Current status of wastewater. Greece and, of course, Crete have to comply with the EU Urban Wastewater Treatment Directive 271/91/EC [95]. Today, the status of wastewater management in Crete has been improved significantly. The total length of wastewater collection system is estimated to be about 3000 km serving more than 90% of the total population. In contrast to the common practice of Cretan ancient periods, where the wastewater and stormwater networks were combined, separated systems have been dominant throughout the island since the middle of the last century.

The current status of wastewater treatment in Crete, based on the population served, is presented in Table 9. Today, there are about 100 operational WWTPs, most of which serve human settlements of less than 2000 inhabitants. Most of these WWTPs are in the eastern part of Crete. As noted in Table 9, most of the remaining WWTPs to be implemented in the future are for small settlements with a capacity of less than 2000 population equivalents (pe) [91]. It has been estimated that more than 80% of the island's population will be served after the completion of all plants with a capacity of more than 2000 pe.

Regarding the technology applied, a number of different WWT technologies have been adopted for use in Crete. Among the WWTPs serving more than 2000 inhabitants, 95% are conventional activated sludge and/or extended aeration systems. For populations of less than 2000 inhabitants, the predominant technologies are gravel and sand filters, textile filters, and constructed wetlands. Furthermore, it should be noted that 5%–10% of the population resides in villages of less than 500 ep for which on-site sanitation technologies are used [91].

4.5.2. Water Reuse

Because of the large number of operating WWTPs in Crete, the potential for water reuse is high (Table 9) [15]. However, at present, the major proportion of the treated effluent is discharged to the sea, instead of being reused for crop irrigation [96], to replenish aquifers [97] and/or to hinder seawater intrusion [67,98]. Furthermore, recycled water can be an extra source of nutrients (mainly nitrogen and phosphate) for the existing cultivations reducing the consumption of conventional fertilizers and, hereby, the overall production cost [17,18]. It is estimated that the use of recycled water could reduce the use of commercial nitrogen fertilizers by 5–7 kg N/year.ha. Of the 99 operating WWTPs (Table 9) serving about 80% of the island's population, only 10.06% of the treated effluent (Table 9) is currently used for crop irrigation.

Several factors are responsible for the limited use of recycled water in Crete. Among them, barriers arising from the strict regulations set by the national and EU legislation and the low social acceptance are considered the most important [99,100]. A typical example of strict regulations is the required monitoring of heavy metals and metalloids. Based on the capacity of the WWTP, monitoring frequency varies from 2 (<10,000 pe) to 12 (>200,000 pe) times per year. Another example is the need to monitor 40 organic compounds at least twice per year in WWTPs serving more than 100,000 ep [99,101]. Recently, the EU proposed guidelines for effluent reuse [102], defining minimum requirements for crop irrigation and aquifer recharge along with monitoring needs. The proposed criteria define water quality classes depending on the intended use of crops and irrigation method based on BOD/COD thresholds and *E. coli* population (10 up to 10,000 cfu/100 mL). Furthermore, it has been proposed to consider limits for specific parameters, including heavy metals, pesticides, disinfection by-products, pharmaceuticals, and other substances of emerging concern, and anti-microbial resistance [102]. Finally, it is required for operators to establish a risk management plan to ensure addressing of the potential additional dangers [103].

Reuse has low public acceptability in Crete mainly due to pricing and environmental/public health issues [100]. Raising the awareness of the stakeholders and farmers is probably among critical options for authorities [100]. However, given the presence of harmful substances in the effluents, further steps should be taken to revise the water quality criteria list. Moreover, it is important to develop and introduce a new pricing policy for non-conventional waters, as well as new certification processes along the product chain and a uniform labeling policy to ensure that products in the market are safe.

Certification is in agreement with current framework covering the production delivery and marketing of the conventional products and the new EU policy.

Table 9. Current status of wastewater treatment in Crete (adapted from region of Crete) [104].

Population Served	WWTPs (no)	Capacity (hm ³ /Year)	Reused (hm ³ /Year)	Reuse Opportunities	Comments
<2000	67	3.90	0.75	Agricultural irrigation.	Numerous additional small projects (more than 650 ^a) serving less than 2000 persons are in various stages of planning and development. When completed, these treatment plants will serve 15%-20% of the total population of Crete. Two more plants are under implementation and three are under construction. One more plant remains under implementations and another one is under construction. When those treatment plants (including the above) are completed, the total population served will rise above 80%.
2000–5000	15	4.65	0.90	Agricultural irrigation and landscape irrigation.	
5000–15,000	10	8.90	2.25	Agricultural irrigation, landscape irrigation, and groundwater recharge.	
15,000–100,000	5	12.00	0.55	Agricultural irrigation, landscape irrigation, groundwater recharge, and indirect and direct potable reuse.	
100,000–150,000	1	10.20		Agricultural irrigation and landscape irrigation.	
>150,000	1	14.50	1.00	Agricultural irrigation, landscape irrigation, groundwater recharge, and indirect and direct potable reuse.	
Total	99	54.15 ^b	5.45 ^c		

^a WWTPs under implementation are not included. ^b The potential for agricultural use is about 10.1% of the total water used for agricultural irrigation [15]. ^c About 1.10% of the water is now used for agricultural purposes.

Based on the above discussion, it can be argued that Crete has the potential to increase significantly the use of recycled water in the coming years, by providing further services and benefits to the economy, natural resources, and the environment. Achieving the above goal, however, presupposes the resolution of key issues, such as those that meet the quality standards of outflows (revised criteria), pricing policy of their use, as well as certification issues for the products produced. It should be emphasized that all actions as a whole should be compatible with current national and EU policies and requirements for sustainable resource management, sustainable agriculture, the development of the circular economy, and adaptation to climate change. Overall, the expansion of water reuse in Crete is expected to have a number of positive impacts for the residents, the local economy, and the environment that can be summarized as follows:

- Improve water availability and strengthen the adaptation potential to climate variability;
- Support crop production and reduce production cost by water and nutrients supply;
- Enhance the transition toward circular economy agricultural practices;
- Reduce pollution risks for water resources;
- Protect groundwater, the major current source of irrigation water, from overexploitation and degradation.

4.5.3. Brackish Waters

Brackish water is a significant source of water in Crete that could be exploited potentially for variety of different applications. Only the well-known sources of brackish springs, developed in karsic formation, known as Almyroi (e.g., Almyros of Iraklion, Almyros Agios Nikolaos, Almyros Georgioupolis, and Malavra spring) around Crete exceed the 1000 hm³/year [105]. For instance,

the Almyros in the Iraklion city releases on an average basis 250 hm³/year (ranging from 5 to 7 m³/s in dry and wet period, respectively), which exceeds 50% of total annual water needs of Crete. To date, these sources of water remain unexploited. The use and exploitation of water resources in karstic formation through the centuries, especially in the Mediterranean area, has been studied widely in the literature [106]. The knowledge of the historical techniques of karst water exploitation is significant for better management and planning of water resources under scarcity in the island. A brief synthesis of the numerous investigations carried out in the Almyros spring of Iraklion, obtained with a view to determining practical methodologies for capturing fresh water, follows.

- (a) The major hydrological characteristic of the Almyros spring is that the water becomes brackish under low flow rates (less than 12 m³/s), i.e., about nine to ten months per year. The total dissolved solids (TDS) decrease from a maximum concentration of 5 g/L in October to less than 0.30 g/L during the following maximum discharge flow rate. Water from Almyros spring could serve Iraklion city with potable water for 35–45 day/year when the concentration of TDS remains below 0.30 g/L. The possibility of constructing a reservoir outside of Almyros basin (e.g., Taveronas basin) for storing the produced fresh water, when the TDS concentration is less than 0.30 g/L, and using it for water supply of Iraklion municipality has been evaluated [107]. An exploitable volume of 31.10 hm³/year of fresh water, to be stored during the 30 day/year (conservative forecast) when the maximum discharge flow rate is greater than 12 m³/s.
- (b) Several investigations have been carried out since 1964 to understand the spring function mechanism and reduce the seawater intrusion in the Almyros karstic system [108,109]. A small dam was constructed in mid 1970s (Figure 9) based on a previous study [110]. The objective of the dam to raise the water up to 10 m above the sea level to increase the hydraulic pressure in the karstic system and to reduce the seawater intrusion. The experiment was carried out at the end 1977, just for a few days, due to a sudden flood event. Based on the data obtained, no improvement was found in the spring water quality. However, in another experiment, carried out from 12 February to 15 September 1987, significant TDS concentration reductions were assessed [106]. In an earlier study, the operation of brackish karst springs was simulated with the MODKARST model. The simulations revealed that sea water intrusion depends on the difference between the freshwater and seawater density. Moreover, with regard to chloride concentration during the depletion period, the difference is due to the lower pressure in the freshwater channel compared to the channel carrying the seawater [111]. Another study reported that the sea intrusion could be prevented by raising the spring water outlet, through the construction of a new dam of an estimated elevation of 26 m above the sea level [112].
- (c) Recently, it was reported that increasing the height of the dam up to 25 m would minimize sea water intrusion [113]. It should be noted that none of the coastal brackish springs in Crete are 25 m above sea level [114]. Ntaskas (2018) correlates the flow rate of the Almyros spring with rainfall in the Idi (Psiloritis) mountain and the TDS concentration. Specifically, at a flow rate of less than 5 m³/s, the TDS concentration is greater than 5 g/L and at a flow rate above 12 m³/s, it is less than 0.4 g/L. Moreover, the hydraulic pressure in the karstic system under the high flow rates should increase significantly. Furthermore, Ntaskas (2018) found that a dam at an elevation of 25 m, estimated to cost 4 million €, would support a small hydroelectric power plant of 2.4 MW with an annual energy output of 11 million kWh.
- (d) Finally, in another earlier study, the construction of an underground infiltration gallery inland, upstream of the salinization zone, to optimize the exploitation the karstic spring's aquifer (Figure 8) was recommended [115]. Such a project is believed to be a long-term and definitive solution to the water supply problem of the Iraklion municipality and the adjacent villages.

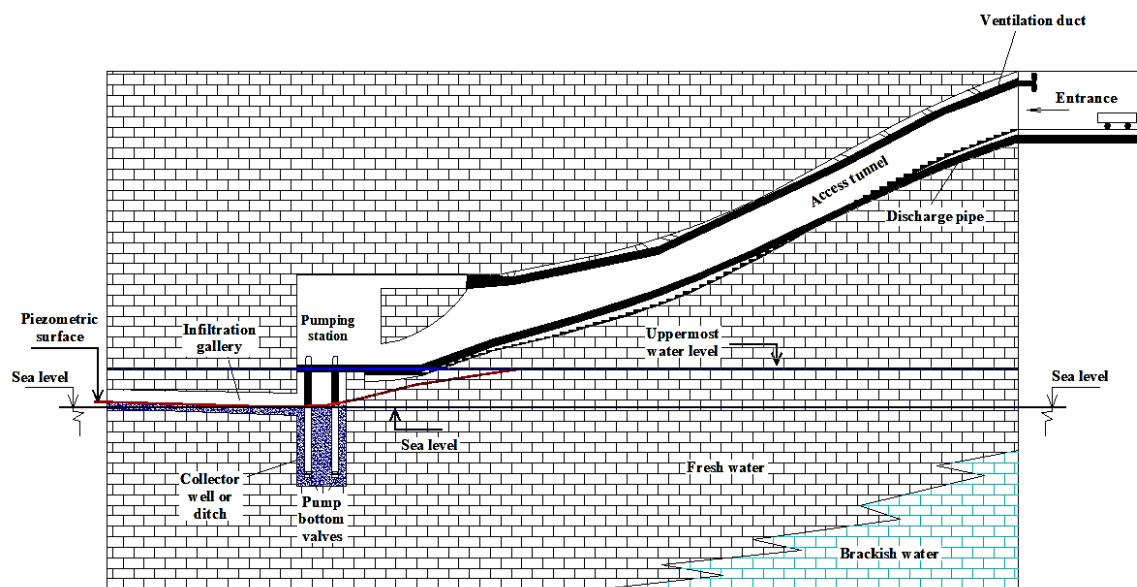


Figure 8. Cross section of proposed underground infiltration gallery (adapted by [87] from [115]).



Figure 9. Almyros spring and the dam with a height of 10 m.

4.5.4. Desalination

Desalination of seawater for the production of potable water has become a popular option, especially in water limited regions [116]. In the past few years, the cost of desalinated water has decreased considerably, while further decreases are expected [117,118] due to advances in membrane technology and improvements in energy conversion coefficient of desalination processes [119].

A new desalination plant has been operated by the Municipal Enterprise for Water Supply and Sewerage of Malevizi, to the west of the Iraklion city, since 2014. Its capacity is 2500 m³/day and includes ultrafiltration and reverse osmosis. The total operational cost for delivered water is 0.24 €/m³. The plant uses brackish water from Almyros spring with a TDS concentration of less than 10 g/L. An upgrade of its capacity to 6000 m³/day was completed recently. Another plant with a capacity of 3500 m³/day is currently under implementation by the Municipal Enterprise for Water Supply and Sewerage of Iraklion. The plant will use groundwater with a concentration of TDS less than 3 g/L

composed mostly of calcium sulfate. Desalination plants should be considered seriously as an option in the regional development plans to avoid unruly development of coastal areas [120].

5. Reorganization of Water Management at Local Level and Water Safety Plans

5.1. Municipal Water Supply and Sewerage Enterprises (DEYA)

The Municipalities (Figure 10) and Municipal Water Supply and Sewerage Enterprises (DEYA) of Crete are responsible for water management at local level. Today, 82.50% of the permanent population is served by the existing DEYA, and the remaining 17.50% is served by the technical services of 12 Municipalities (Table 10). Following the practice of other EU states, either DEYA should be established in the latter, and/or the existing neighbor DEYA should be reformed as Inter-Municipal Water Supply and Sewerage Enterprises (DDEYA) for serving the remaining 17.50% of Crete's permanent population. Such a proposed scheme is shown in Table 10.



Figure 10. Municipalities in Crete.

Table 10. The existing 24 Municipalities, the 12 Municipal Water Supply and Sewerage Enterprises (DEYA), the proposed 9 DEYA (including the existing ones), and the 7 Inter-Municipal Water Supply and Sewerage Enterprises (DDEYA).

Municipalities	Existing	Proposed
Chania	DEYA Chania	DEYA Chania
Platanias	DEYA North Axis	DEYA North Axis
Kantanos-Selino	DEYA Kantanos-Selino	DDEYA Kissamos-Kantanos-Selino
Kissamos		
Apokoronas		DDEYA Apokoronas-Sfakia
Sfakia		
Gavdos		DEYA Gavdos
Rethymno	DEYA Rethymnon	DEYA Rethymnon
Mylopotamos	DEYA Mylopotamos	DDEYA Mylopotamos-Anogeia
Anogeia		
Amari		DDEYA Amari-Agios Vasilios
Agios Vasilios		
Iraklion	DEYA Iraklion	DEYA Irakliou
Malevizi	DEYA Malevizi	DEYA Malevizi
Hersonisos	DEYA Hersonisos	DEYA Hersonisos
Phaistos	DEYA Phaistos	DDEYA Phaistos-Gortys
Gortys		
Arhanes-Asterousia		
Minoa	DEYA Minoa	DDEYA Minoa-Arhanes-Asterousia-Viannos
Viannos		
Agios Nikolaos	DEYA Agios Nikolaos	DDEYA Agios Nikolaos-Plateau Lasithi
Plateau Lasithi		
Ierapetra		DEYA Ierapetras
Sitia	DEYA Sitias	DEYA Sitias

5.2. Water Safety Plans

The SARS-CoV-2 virus causing COVID-19 has not yet been detected in drinking water resources; its transmission by water has not been confirmed, and there is no accepted evidence on the survival times in either drinking water or wastewater and under what conditions. However, if another hydrophilic microorganism is present, it potentially could transmit it. Thus, water agencies should prepare for the worst, "even if it is unnecessary." As the COVID-19 is an invisible enemy, every effective means should be used to deal with it such as:

The virus is not a living organism; it consists of a protein and RNA molecule covered by a protective layer of lipid (fat). The survival time depends on external factors, such as temperature, humidity, exposure to sunlight, and type of hosting material. The virus is controlled by soapy water, which should be available to all citizens as the best protective medicine against COVID-19.

- a. Drinking Water Services should prepare Water Safety Plans in each DEYA to ensure the quality of drinking water in accordance with the guidelines of Directive 98/83/EU [121] and those of the World Health Organization (WHO) [122] for the quality of drinking water. These plans are considered to be the most effective means for continuously ensuring the safety and acceptance of drinking water supply. They require a risk assessment, which includes all the necessary steps in water supply from the catchment to the consumer, followed by the implementation and monitoring of risk management control measures, with emphasis on high-risk hazards.
- b. Moreover, plans must be developed for water management, mainly for operation of water supply infrastructures under emergency conditions. Such an Emergency Plan has been recently prepared by the Development Organization of Crete (OAK. SA), which can be considered as pioneering, if not at European, certainly at a national level [123]. Well done to those who designed and implemented it, even if it may be unnecessary; *κάλλιον το προλαμβάνειν ἢ το θεραπεύειν*, i.e., "it is better to prevent than to cure," Hippocrates (460–370 BC).

6. Water and Energy

Generally, energy and water are inextricably linked. Energy production and generation require water and water use, e.g., pumping, treatment, and distribution require energy. In Crete, awareness of the close relationship between water and energy is raising. The number of new approaches being proposed that will lead to energy security and water sustainability is significant. Discussions and preliminary studies are on the way for further improvement and exploitation of existing water bodies, mainly dams for touristic and energy purposes, as it happens abroad, e.g., in the famous Hoover Dam in California; now, this is the focus of a distinctly 21st-century challenge: turning the dam into a vast reservoir of excess electricity fed by the solar farms and wind turbines that represent the power sources of the future [124].

In Crete, such an energy exploitation of the Potamon dam Pumped Hydro-storage (PHS) system is under implementation. The project consists of a PHS (Figure 11) with a guaranteed power of 50 MW. The renewable energy sources consist of two wind farms with a total installed capacity of 89 MW in the municipality of Sitia in the eastern part of Crete and a water turbine production unit consisting of three reversible fixed speed units with a production power of 50 MW and pumping power of 108 MW [125,126]. The lower reservoir is the reservoir of the existing dam in the municipality of Amari, while the upper reservoir with a capacity of 1.15 million m³ is located in the area named Gargani in the municipality of Rethymnon, with a height difference of 450 m and a distance of 2.5 km [125]. The PHS will produce 227 GWh hydro-energy annually delivered to the isolated electrical grid of Crete. It will contribute greatly to the further integration of renewable energy resource in Crete and to the stabilization of the electrical network, as the electricity generation is guaranteed. Reductions in pollution from existing conventional Public Power Corporation power plants in Crete are significant [126,127].

Given the current experience and knowledge gained by Potamon dam PHS, there is the option to expand it to other existing water infrastructures, e.g., Aposelemis or other dams, water network, etc. Aposelemis dam has been already the subject of a feasibility study regarding the implementation of a hydroelectric project, indicating, however, the need to consider and address critical socio-economic and environmental issues [128]. Beside dams, specified points of the main irrigation network of Crete, which satisfy the technical requirements (e.g., height difference and water speed and pressure), can be exploited for energy production by using the pumping technique commonly used in small hydroelectric systems. [125]. Recently, Katsaprakakis et al. (2019) reported that Crete has both the renewable energy sources (RES) potential (both wind and solar radiation) and the appropriate land morphology for PHS installation required for the development of the fundamental electricity production and storage plants for high RES annually, for turning itself into an energy independent island [129].

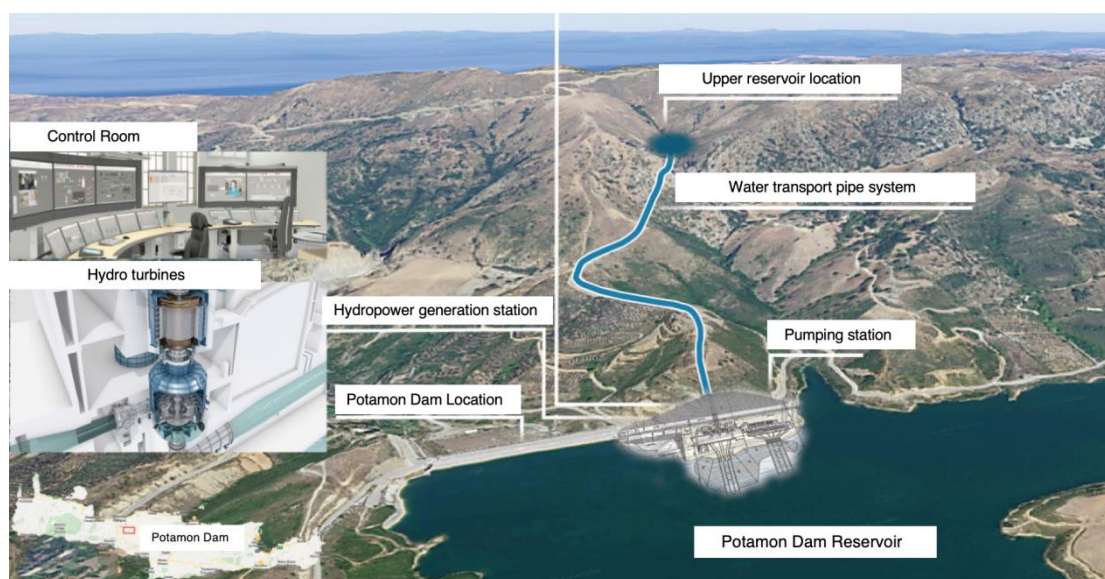


Figure 11. Schematic representation of Pumped Hydro-storage (PHS) in Potamon Dam (modified from [130]).

7. Water Sustainability Issues and Opportunities

In Crete, the sustainable use of water resources seems to have its roots in the ancient civilizations and Minoans, as evidenced by their advanced technological water and wastewater achievements [21,131]. Today, increased water demands to meet the needs of agriculture and tourism and the pressure of climate variability, underline the need to re-consider existing water management plans and practices by adopting an integrated water management plan (IWMP) for the Island of Crete and governance tools that consider all the available sources of water. The need for the sustainable use of water resources is still a critical issue for Cretan, Greek, and EU governances aiming at a water efficient society for the benefit of water resources and environment, safe water supply, and sustainable (circular) economy [15,94,132]. Topics that should be considered in the development of an IWMP are as follows.

7.1. Uneven Availability of Water Resources

Despite the overall water sufficiency of Crete, there are regions (Messara valley, Sitia area) that experience severe water shortages, especially during the summer, due to increased residential and agricultural needs [13,133]. To address these water imbalances, short-term and long-term strategies and appropriate measures are necessary to close the gap between water availability and consumption enabling long-term protection and sustainable use of water resources. For example, to increase water availability, use of other water resources (e.g., distant or neighboring lagoons or dams, recycled water, rain harvest water, etc.) should be under consideration ensuring, however, that it satisfies specific

social-economic, environmental, and climate prerequisites and requirements [132]. The former means that, beside environmental and climate, issues and measures depicting the cost-benefit value and public acceptance and compliance should also be considered and be taken into account [134]. An example of exploitation of distant or neighboring lagoons or dams, despite the planning and management problems, is the current use of water of Faneromeni and Aposelemis dams located in areas characterized by intensified agricultural production. To protect groundwater aquifers from overexploitation and deterioration, aquifer protection measures should be applied (e.g., reduced abstraction, replenishment with treated effluent or rainwater to increase their capacity or protect them from seawater intrusion). Moreover, it is necessary to establish limitations and prohibitions, particularly in vulnerable areas, relying on an intensified monitoring plan against depletion and chemical pollution (e.g., nitrates, organic compounds, etc.) [15,132,135].

7.2. *Efficient Water Use in Agriculture*

Reduction of water consumption in agriculture seems to be crucial to reduce or even reverse negative imbalance events and eliminate the pressure on groundwater resources in Crete (Table 4). So far, water pricing (e.g., tariffs) and/or non-pricing (e.g., field practices, awareness campaigns, education, etc.) measures are proposed to achieve minimum possible use of water in parallel with the minimum possible losses to the environment (illustrated by increased water use efficiency). To enhance the efficiency of water use in the agricultural sector, a number of actions should be taken including: the modernization of irrigation systems, the adoption of modern methodologies of ET estimation, adoption of smart agriculture and/or deficit irrigation concepts, testing of crop adaptations to meet water-efficiency and climate variability goals, improved soil management (e.g., reduced tillage, residue recycling), and develop practices increasing the small farms resilience under water scarcity.

7.3. *Low Agricultural Water Use Efficiencies*

In addition to the above, water volumetric pricing policies should be used by local agencies to improve water use efficiency in the fields, by controlling the use of water, crop adaptation, and field practices. However, volumetric pricing requires strict control, metering, and a pricing policy to provide incentives or disincentives (based on pricing levels) for those with low or high-water consumption, respectively. Current records indicate that volumetric pricing policy (0.05–0.65 €/m³) is quite common in water management in Crete. However, there are variations across the island depending on the managing agency policy, geographical region, origin, and the quality and quantity of water [13]. Moreover, there has been significant mismatch between the water use history and the corresponding applied pricing policy attributed mostly to inadequate or imposed estimates by managing agencies. Finally, the proposed measures and practices may require regulatory adjustments, development and adoption of new technological innovations (e.g., new technology for accurate irrigation, effective monitoring of plants water status and soil moisture, overall water management by managing agencies and authorities, etc.), and cooperation schemes as well as support by diverse finance tools. EU (and national agricultural policy) either via Common Agricultural Policy (CAP 2014–2020) or other relevant policies (e.g., circular economy concept) provides the legislative framework and the wide spectrum of financial tools aiming at directed knowledge and innovation via collaborations among universities' research institutions, private sector, and (groups of) farmers in agri-food sector.

7.4. *Non-Revenue Water Losses*

Non-revenue water supply is another important issue that should be considered and properly faced by responsible agencies and authorities describing mainly the losses via supply and distribution networks, the illegal connections, and the unbilled authorized use. It is worth noting that non-revenue water in Crete may exceed 60% of the availability potable water supply, highlighting it among the critical issues of water management for the decision makers and authorities.

7.5. Limited Water Reuse

Water reuse in Crete can increase water availability in many problematic areas of the island and contribute to a far more efficient use of water, mitigating in parallel the negative impacts from over-exploitation of subterranean water. Water reuse can also be seen as an additional way to cope with climate variability, as well as to comply with the circular economy concept [136], which are rapidly expanded across EU economies. The geographical distribution of the WWTPs across the island is appropriate for water reuse. Despite the current legislative framework, more work needs to be done with respect to food safety, public acceptability and marketability. Indeed, current EU and national policy supports this direction in many different ways either by providing the legislative framework [101,102] or the necessary economic tools; however, there are still certain issues that need to be addressed, such as legislative requirements (e.g., quality criteria) governing wastewater treatment and reuse, inadequate legislation covering the product value chains, lack of incentives (low pricing levels) for the users, consideration of the potential capital and operating costs of switching to reclaimed wastewater, uncertainties in the quality of the effluents and products; all are considered critical drivers of safe and economically efficient reuse of reclaimed wastewater. All these factors are drivers of public acceptance.

Additional issues can be the available and continuity of the wastewater supply, quality of services by involved agencies, reliability of supply, and adoption of the proper pricing systems; these should be described by agreements between the supplier of reclaimed wastewater and the customers. To date, most of the above issues that interact inevitably with each other have not been outlined or identified fully. It appears that what is needed is targeted research (including environmental and social-economic assessments) and effective corporations and synergies among stakeholders, supported by national or EU funding tools. An example of a critical issue could be the regulatory gap on specific emerging pollutants/contaminants, such as disinfection byproducts, pharmaceuticals, or anti-microbial resistance that are commonly found in municipal wastewater effluents [137,138]. These substances could be moved through the trophic chain and threaten terrestrial and aquatic biodiversity and humans' health [136,139]. Altogether, reuse in Crete clearly lags behind other regions or countries due to weak regulatory framework and governance of water and sanitation sectors, lack of incentives (low pricing policy), and low public acceptance. By solving the regulatory issues and providing incentives (mostly focused on low wastewater effluent prices) public acceptance and private sector would probably move towards water reuse, favoring in parallel the application of decentralized/small onsite treatment systems. These systems could be a boosting leverage for water reuse in the island, allowing the exploitation of wastewater on the site of their production [140].

7.6. Limited Use of Alternative Water Sources

Water storage, desalination, water and rainwater harvesting could be seen as alternative complementary water sources in Crete, particularly when other, more cost-effective resources are insufficient. European experience [135] indicates that these alternatives can have a role in water management and may help in local water balances; however, detailed planning strategies and measures are required, supported by a regulatory framework, investments, and relevant research. In Crete, there is lack of experience on rainwater harvesting, an issue that remains unexplored; however, several proposals like greenhouse rainwater collection are considered [134]. Moreover, the use of Almyros River water particularly in winter months, when the salt concentration is low, should be considered and supported. Previous and recent investigation have highlighted options and solutions for decision makers, such as the construction of dam, to increase the water availability and reduce its degradation by seawater intrusion [113,114]. Moreover, another option may include desalination of salty waters which is now more feasible due to new technological advances [119], probably, small-scale desalination plans for low population areas and higher-scale ones in northern urban areas. Beside the above, for non-conventional water resources, it is also speculated that potable water reuse might be a critical element in the development of sustainable strategies for water supply in the future, particularly in

areas with high density population (i.e., those existing in northeastern part of the island). Such an option may seem more viable over the withdrawal of transportation and final discharge of the water of the inland areas.

7.7. Water and Energy Production Nexus

Finally, efforts should be done towards the connection of water with energy production initially by exploitation of existing infrastructure (i.e., dams and water networks) for energy purposes. Of particular importance is to document and highlight the potential benefits and implications for energy reserve, economy and environment over the current situation that relies on operation of Public Power Corporation power plants. The implementation of the Potamon dam PHS, described in detail above, could be a good example and opportunity for the robust assessment of the benefits and drawbacks from such an alternative and may help to expand and enhance water-energy connection along the island, e.g., exploitation of Aposelemis or others dams.

7.8. Local Water Management

Local water management is undoubtedly the concern for all decision makers to ensure a fair settlement of the complex water issues. However, it is important that any solutions be a part of a broader regional and integrated strategic plan that serves primary goals and objectives according the needs of the island. The current water management plans for the RBD of Crete [14,15] could be seen as such, however, additional strategies, systematic recording policy of water resources, estimates on water demands and research findings by regional and local authorities, academic institutions, and private enterprises as well as conclusions by public consultation processes should further be incorporated in the scope of an integrated plan construction. It is remarkable that even though there is solid body of literature and knowledge on water issues of Crete, some of which is presented within this paper, it is yet to be used appropriately to identify and address important current or future problems, in the context of improved and more sophisticated water management. A schematic representation of water uses, proposed measures and key actors and managers of water management in Crete is illustrated in Figure 12.

7.9. Knowledge Gaps

Records in knowledge gaps, particularly those addressing current sustainability issues, are also valuable and can provide the basis for future initiatives and directions. From that point of view and for the purposes of this study what has been highlighted is the need to substantially enrich our knowledge on the links between current water resources status (quality and availability) with the economic, cultural and environmental, and human health performances of the areas, in the context of increasing the public awareness and develop more “clean” and water efficient societies. In this line it is also important, to provide links between water status and the terrestrial and aquatic life and biodiversity, including the protected species and areas, due to their multifaceted role in ecosystems and human well-being [141]. The critical topics and impacts by the current water management along with proposed measures and funding sources, discussed previously are summarized in Appendix A.

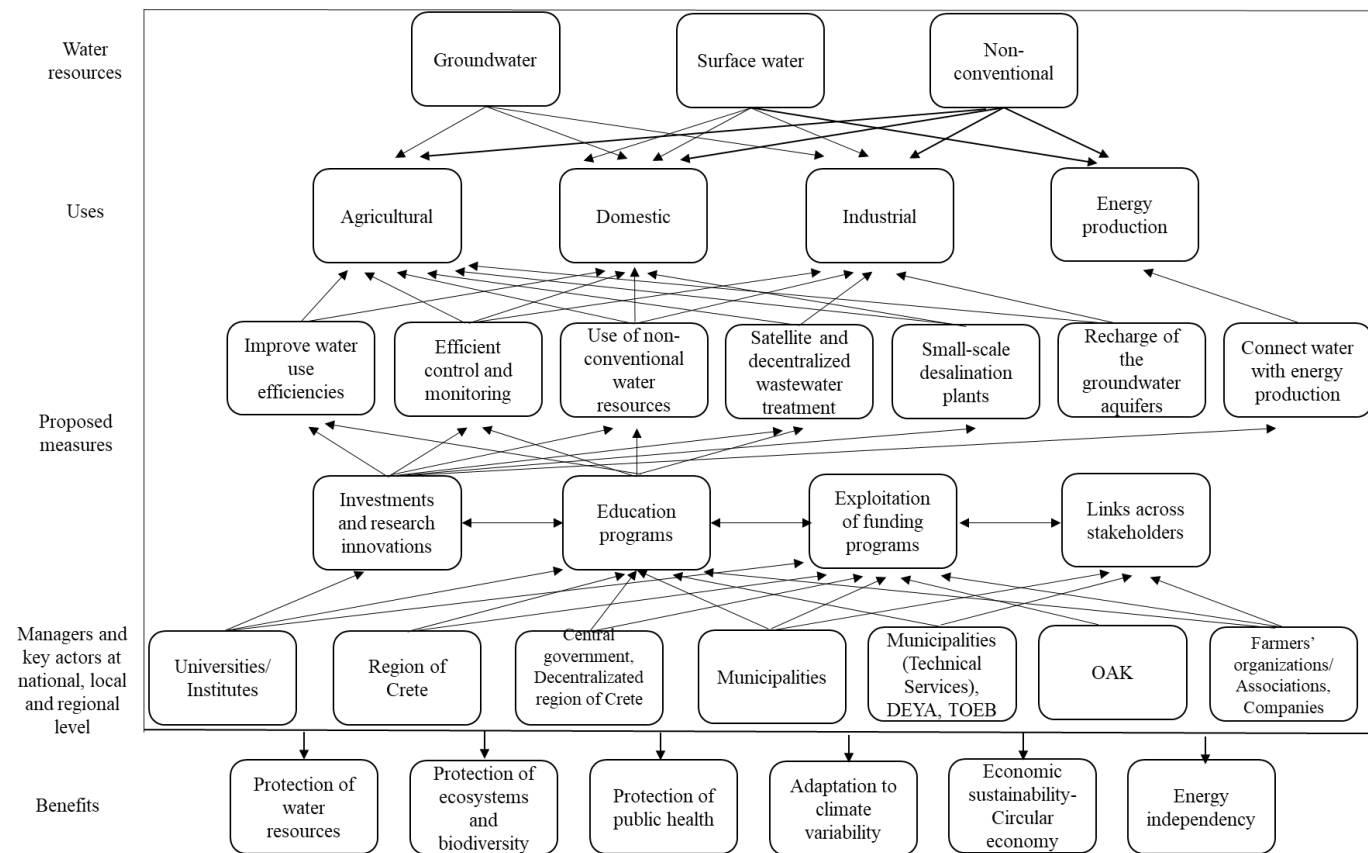


Figure 12. Schematic representation of water uses, proposed measures, and key actors and managers of water management in Crete.

8. Epilogue

Through the long history of the island of Crete, the climatic and hydrologic conditions have been characterized by high variability both spatially and temporally. This variability has had a clear impact on the water availability as well as on the human responses to the observed variability. As a result, a number of piecemeal solutions have evolved over time to deal with local water issues. As the impacts of population growth, tourism, agricultural production, other water uses, and climate variability are now becoming understood more fully, it is clear that the implementation of an IWMP for the Island of Crete is crucial if long-term water sustainability is to be achieved. Important areas of water management that must be addressed in any IWMP, as discussed in this paper, include:

1. Uneven availability of water resources;
2. Over-exploitation of groundwater;
3. Low agricultural water use efficiencies;
4. High non-revenue water losses;
5. Limited water reuse;
6. Limited use of alternative water sources;
7. Water energy production nexus;
8. Local management concerns.

To address the above issues, the development of an IWMP must be based on the availability of reliable data (systematic recording of water resources and water uses), must take into account contemporary and emerging trends, be in harmony with the guiding principles of sustainable development, must consider the implications of the circular economy, and must include a response plan for the uneven impacts of climate variability. It is hoped that the discussion of these issues, along with the discussion of the islands' water resources presented in this paper will be of value to those charged with the responsibility of developing an IWMP for the island of Crete.

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Appendix A

Table A1. Critical topics, impacts-risks, and proposed measures and funding sources for sustainable water management in Crete.

Critical Topics	Impacts-Risks	Major Goals	Proposed Measures
<ul style="list-style-type: none"> Droughts and water scarcity events [13,56,57,62,142] Mismatches between water demand and water availability (negative water balances) [13,15,39,46,62] Over-consumption of water in the field [13,143] Over exploitation of groundwater [14,15,88] Low performance of water reuse (low use or reclaimed and saline water and rain-harvesting [12,13,143] Inadequate control and monitoring [11,15,41] 	<ul style="list-style-type: none"> Reduction of available water resources [87] Depletion of underground water [14,15,88] Increased competition for water High water pricing Reduction in agricultural and livestock productions climate variability impacts- low adaptation potential to [56,59,144–146] Increased water losses 	<ul style="list-style-type: none"> Sustainable water management-Protection of water (and soil) resources [143] Environmental sustainability-Protection of biodiversity, ecosystems and public health [9,147–150] Adaptation to climate variability [143,144,151,152] Sustainable development and economy (strengthen circular economy practices) [53,136,153] 	<ul style="list-style-type: none"> Integrated water management plan [132,152] Detailed records of water resources and accurate estimations (short and long-term) for water demand (including the minimum water quality) for each sector included in a unified platform (including mapping of climate data, water resources and problematic areas) [11,73,154] Efficient control and monitoring framework by farmers, managing agencies and public authorities Adoption of practices that increase water use efficiency in fields (efficient irrigation methods such as accurate or deficit irrigation, crop adaptations, reduced soil tillage, preservation and enhancement of soil organic matter etc.) [77,78,143,155,156] Improved water pricing policy (use of disincentives) [13,79,143] Improved re-distribution of water across different sectors and users. Increase in use of alternative water resources-Adoption of specified measures (low pricing policy, development of criteria and expansion of legislation to ensure the quality and marketability of the products) [13,99,157–160] Establishment of satellite and decentralized wastewater treatment management [140,161]
<ul style="list-style-type: none"> Lack of systematic records of water resources and estimates in water use efficiency and water demands Low linkage among stake holders (e.g., farmers, enterprises, corporations, institutes, universities)-targeted scientific research Adaptation to climate change [56,59,77,143] 	<ul style="list-style-type: none"> Pollution of groundwater [162] Increased risk for sea intrusion risk [72] Increased risk for the terrestrial and aquatic biodiversity [146,163] Increased risk for human health [139,164] 		<ul style="list-style-type: none"> Expansion of small-scale desalination plants (large-scale plants should be implemented particularly in coastal urban areas in the eastern Crete for production potable water, e. g. Iraklion and Agios Nikolaos cities) [117,118,120] Recharge of the groundwater aquifers targeting either the enrichment of the groundwater supplies, or their protection/restoration from seawater intrusion should be seriously considered particularly at the coastal areas of the island [72,87,97,98] Managed aquifer recharge in association to reservoir management Connect water with energy production [125–128] Investments and research innovations in [99]: <ul style="list-style-type: none"> i. water management and monitoring, ii. development of efficient water use practices in the field iii. study the links between water management practices and impacts on environmental, economic and cultural performances and impacts on biodiversity and ecosystem services), iv. Development of criteria for non-conventional water resources Strengthen the links across stakeholders (e.g., farmers, enterprises, corporations, institutes, universities) to address critical issues in water management and increase the use of non-conventional water resources [134] Education programs for the stakeholders [134] Exploitation of EU, national and regional funding tools

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