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Cyprus Surface Water Area Variation Based on the 1984–2021 Time Series Built from Remote Sensing Products

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Abstract: Cyprus experiences the highest level of water stress among European Union countries due to several interplaying factors such as rainfall variability and increasing water demand. These instigate the nation to build dams on almost all rivers of the island to satisfy the requirements for drinking water and irrigation. Many studies have been primarily conducted on assessing water availability for various uses, particularly for drinking water supply and irrigation. However, there is still a gap/less explored area in terms of a better understanding of changes in surface water over time. Thus, this study aims to evaluate the water surface area variation in Cyprus over the past four decades based on remote sensing products, timeseries analysis and trend detection. The result reveals a statistically significant increasing trend ($p < 0.05$) in water surface area between 1984–2021. However, following the completion of the final reservoir in 2010, a statistically significant decreasing trend ($p < 0.05$) was observed in the permanent water surface area. This decline is related to both climatic variability and increased water demands. We observed cycles of 6, 8, and 11 years in permanent water. These cycles indicate a recurring pattern of water scarcity, with severe implication already observed on both economic activity and agriculture. The recent decade has witnessed a decline in rainfall, and this is evident through the decrease in vegetation greenness in rainfed agricultural regions, highlighting its impact. Therefore, the findings of this study underscore not only the necessity for the development of infrastructure aimed at conserving water, but also reinforces the need to discuss water use priorities in Cyprus.

Keywords: water storage; time series analysis; trend detection; Google Earth Engine; remote sensing

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1. Introduction

The relationship between humans, ecosystems, hydrological processes, and biogeochemical cycles forms an interconnected global social–ecological system where social and economic needs have intensified the strain on water resources. An increased demand, combined with the depletion of groundwater reserves and freshwater sources, has led to reduced availability, constraining water uses [1–3]. The issue of water scarcity poses significant challenges to sustainable development and the safeguarding of essential ecosystem functions [4,5].

Estimates indicate that two to four billion people experience severe water scarcity conditions for at least one month annually [6]. Climate change will exacerbate the already substantial impacts of water scarcity on agriculture, energy production, and many other activities [7]. With projected magnification in both the frequency and severity of droughts and floods [8,9], water shortage is becoming one of the foremost global concerns in relation to food production [10].

Decreased rainfall has a direct impact on declining vegetation greenness, as evidenced by a decrease in the Normalized Difference Vegetation Index (NDVI). This decline in NDVI signals reduced vegetation health and productivity, which can have far-reaching ecological and agricultural consequences, including potential food security issues and environmental degradation [11,12].

Water resource management is a global challenge given the complexity in terms of water availability and its uses. For example, while water resources in Northern European countries are generally abundant, Southern Europe often faces scarcity conditions, further affected by high demand for residential supply, irrigation, industrial usage, and tourism [13]. In order to regulate water uses, the European Union has established the Water Framework Directive, aiming at achieving good ecological status for all water bodies by 2027.

Among European countries, Cyprus faces the most severe level of water stress [14,15]. The island experiences severe water scarcity, exacerbated by a combination of factors like high evaporation rates, limited natural reservoirs, and irregular rainfall patterns [16]. Additionally, rapid urbanization and expanding agricultural practices have heightened the demand for water resources. Overall, Cyprus serves as a compelling example of a region actively seeking sustainable solutions to address its specific water resource constraints.

The country traditionally relies on water reservoirs to collect and treat rainwater destined for human consumption [17]. More recently, seawater desalination plants (1997) [18] and the use of recycled water (1998) for irrigation purposes [19,20] were introduced. Furthermore, the island has been surpassing the established ecological threshold by excessively exploiting groundwater resources [21].

Since 1900 up to 2010, Cyprus has constructed a total of 108 dams across nearly all its rivers, earning the country the top position in the European International Commission on Large Dams registry [22]. Several authors have studied these reservoirs, including their thermal stratification [23], the occurrence of fish species [24], water quality [25–27] and wetlands (including dams) [28]. On the other hand, a gap identified in the literature is how the water surface changes over the years, not only the reservoirs but all water bodies. Is it possible to observe trends and recurrence cycles?

Monitoring water resources can be an expansive and demanding task when measurements are taken from the environment. Moreover, in situ data are generally a punctual measurement, sometimes outdated or, even worse, unavailable. In this context, satellite products provide a synoptic view of watersheds, enabling periodic detection of changes in land cover and land use, including surface water extent. In the same way, geographic information systems, statistical techniques, and cloud-based services can further enhance the processing capabilities of remote sensing products, allowing for the integration of spatial data and time-series analysis.

In this sense, the objective of this work is to evaluate the water surface variation in Cyprus over almost four decades (1984–2021), before and after the construction of its last dam in 2010. We have addressed those questions by using remote sensing and statistical techniques to analyze an extensive database. Our findings indicate the occurrence of water scarcity cycles and provide insights into water management.

2. Materials and Methods

2.1. Study Area

Located in the Mediterranean Sea, the island of Cyprus is positioned (Figure 1) east of Greece (270 km), south of Turkey (70 km), and west of Syria (110 km). Spanning an area of 9251 km^2, with 5760 km^2 under the jurisdiction of Republic of Cyprus. The island's coastline stretches for a total length of 772 km.

The morphology of Cyprus is shaped by four prominent landforms: (1) The Troodos Mountains, situated in the central-western part of the island, encompassing the highest peak, Mount Olympus, and reaching an elevation of 1951 m above sea level. (2) Pentadaktylos, running along the northern coast, is a relatively narrow range with peaks reaching altitudes of up to 1000 m. (3) The Mesaoria central plain is located between the Troodos and Pentadaktylos mountain ranges and features low-lying terrain, and (4) along the coastline, there are coastal plains and valleys that extend alongside the shore [29].

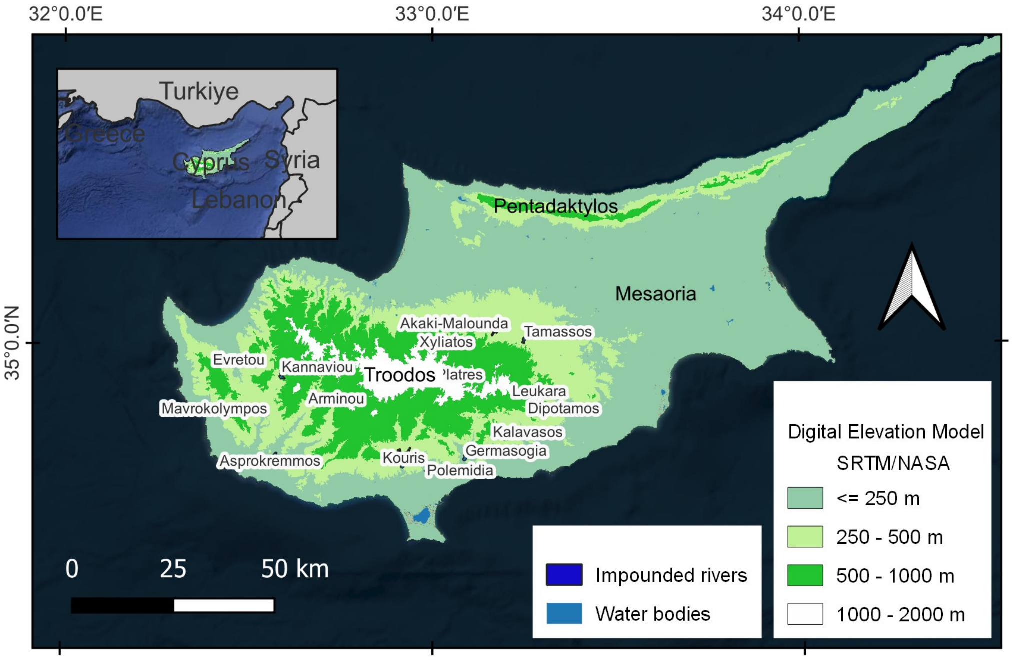

Figure 1. The location and topography of the study area. Source: This map was generated by the authors using the open-source software QGIS version 3.24.

Cyprus experiences a Mediterranean climate characterized by distinct seasonal variations in temperature and precipitation, featuring mild winters and hot summers [29]. Precipitation data were obtained from the Water Development Department (WDD), with records available from 1901 to the present. The data were grouped by hydrological year and the climatological average for each 30-year period was calculated.

The hydrological year on the island commences in October, and the wet period lasts until April. Rainfall levels fluctuate depending on the latitude and altitude. In Ammochostos, located at the eastern end of the island, the average annual rainfall stands at 320 mm. However, as one moves westwards, such as in the Paphos district area, the average annual rainfall increases to 540–550 mm. On average, approximately 80% to 85% of the precipitation is returned to the atmosphere, with evapotranspiration rates potentially reaching 95% during drier years [29].

2.2. Remote Sensing Products

Remote sensing techniques are able to delineate the surface water in various ways [30–33]. Advancements in computing capabilities have played a vital role in shaping this field in the last few years. Furthermore, there are now multiple globally available analysis products that facilitate the examination of changes in surface water area dynamics [34,35]. In this way, the changes in surface water area can serve as an indicator for water storage [36]. Figure 2 illustrates the methodological sequence flow used in this study.

The dataset "Global Surface Water", derived from remote sensing, was used in this work. The product is derived from Landsat series imagery, covering the period from 1984 to 2021. The dataset is available in Google Earth Engine (GEE) {ee.ImageCollection("JRC/GSW1_4/YearlyHistory")}. Each image contains a band with values from 0 to 3 that mean "no data", "not water", "seasonal water", and "permanent water", respectively. A permanent water surface is characterized by water presence year-round, whereas water is deemed seasonal if the months with water presence are fewer than the months with valid observations [37]. Pekel et al. (2016) report temporal data gaps in some regions because Landsat 5 lacked on-board data recorders, and its data transmissions to ground stations relied on other satellites that experienced failures over time [37]. Consequently, our dataset spans from 1984 to 2021, with missing data in the years 1988, 1989, and from 1991 to 1997 due to unavailable images.

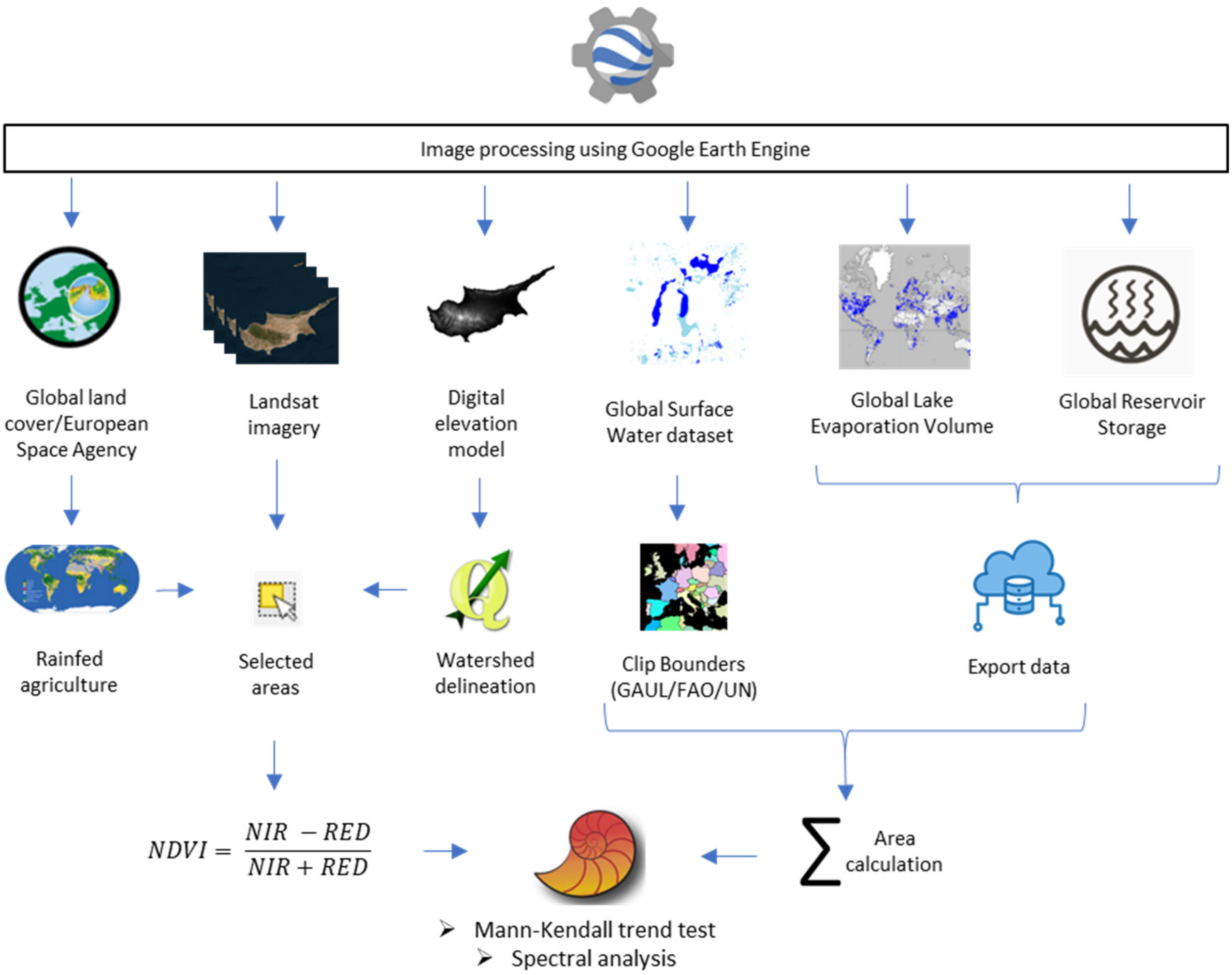

Figure 2. Summary of the workflow followed in this study. The Normalized Difference Vegetation Index (NDVI) is calculated by using remote sensing images from the near infrared band (NIR, 0.85–0.88 µm) and the red band (RED, 0.64–0.67 µm), in the case of Landsat 8.

The images were clipped by the administrative boundaries of Cyprus from The Global Administrative Unit Layers provided by The Food and Agriculture Organization (FAO) from the United Nations, also available at GEE {ee.FeatureCollection("FAO/GAUL/2015/level0")}. The surface areas were calculated considering only polygons larger than 1800 m^2 (2 Landsat pixels).

Volume area information of the main reservoirs in Cyprus was obtained through the Global Lake Evaporation Volume and Surface area dataset [38] and the Global Reservoir Storage dataset [39]. These sources corroborate one another as well as the Global Surface Water dataset [37], which allowed us to go further by examining trends and periodic occurrences based on not only this database, but also based on in situ precipitation records and NDVI image processing to analyze the impacts on rain feed agricultural fields.

To evaluate possible vegetation responses depending on water availability, the Normalized Difference Vegetation Index (NDVI) was calculated for the island of Cyprus, using the entire Landsat historical series from 1984 to 2021. Atmospherically corrected surface reflectance products were used to ensure compatibility and consistency of the time series produced, for example for Landsat 8 {ee.ImageCollection("LANDSAT/LC08/C02/T2_L2")}.

Remote sensing products were acquired and analyzed within the GEE platform, with JavaScript programming being employed through its web-based code editor interface. Some river basins were chosen based on their land use and coverage according to the Global Land Cover product from the European Space Agency, at 10 m resolution based on Sentinel-1 and Sentinel-2 data. To delineate the river basins, altimetric data from the Shuttle Radar Topography Mission were used, with a spatial resolution of 30 m {ee.Image("USGS/SRTMGL1_003")}. Only the altimetric data were processed using the free software QGIS.

2.3. Timeseries Analysis and Trend Detection

After obtaining and processing remote sensing products to produce a time series of water surface areas, the data were subjected to statistical tests to detect trends, in addition to signal decomposition to detect frequencies.

In order to identify trends in the time series of water surface area and NDVI, we used the nonparametric Mann–Kendall trend test. These tests rely on computing a dimensionless statistic (S). The time series is ordered ($x_1, x_2, \ldots, x_n$) and Equation 1 is used to compare the relative magnitudes of the observed data after converting them to signals (Equation 2). A positive value of S implies an upward trend, while a negative value signifies a downward trend [40]. The trend strength is proportional to the S magnitude, also confirmed by the *p*-value (*p*), indicating how likely it is to observe the data if the null hypothesis is correct. So, we have set a significance level of 0.05 for our analysis.

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} sgn\ (x_j - x_k) \tag{1}$$

$$sgn\ (x_j - x_k) = \begin{Bmatrix} 1,\ if\ x_j - x_k > 0 \\ 0,\ if\ x_j - x_k = 0 \\ -1,\ if\ x_j - x_k < 0 \end{Bmatrix} \tag{2}$$

To assess the normality of a distribution, the Shapiro–Wilk test is utilized, producing a test statistic denoted as W. For non-normal samples, the value of W tends to be small. Along with the test statistic, the test also provides a *p*-value. If the obtained *p*-value is less than 0.05, it suggests that the distribution significantly deviates from normality, and the assumption of normal distribution can be rejected [41].

In order to detect frequencies in time series, the Fourier decomposition was used. This technique enables frequency detection from timeseries exhibiting seasonal behavior [42]. Spectral analysis through a Fast Fourier Transform (FFT) algorithm is frequently employed in environmental studies due to its ability to reveal periodic events [43]. Also, power spectral density (PSD) obtained from FFT and represented by periodograms is a recommended approach to detect seasonality [44,45]. Similarly, we employed the Evolutive Fourier transform, a spectral analysis technique that segments the signal and allows for the development of the spectrum over time [46]. This method not only facilitates the detection of frequencies, but also provides information about the timing of frequency occurrences.

3. Results

The results are divided into two periods of analysis, from 1984 to 2021 representing the entire time series (with gaps: 1988, 1989, 1991 to 1997, when images were not available) and from 2011 to 2021, representing the period where no other dams have been built in Cyprus. For the year 2021, we produced 209 polygons delimited as water bodies, and 47 of them are in the occupied northern part of Cyprus.

The Mann–Kendall trend test confirms that the permanent water time series (Figure 3A) exhibits a statistically significant upward trend (S = 152 [dimensionless], $p < 0.05$). This outcome was already expected due to the construction of 18 reservoirs between 1984 and 2021 [45], representing an increase in water surface area. Similarly, the seasonal water time series (Figure 3B) also shows a statistically significant increasing trend (S = 244 [dimensionless], $p < 0.05$).

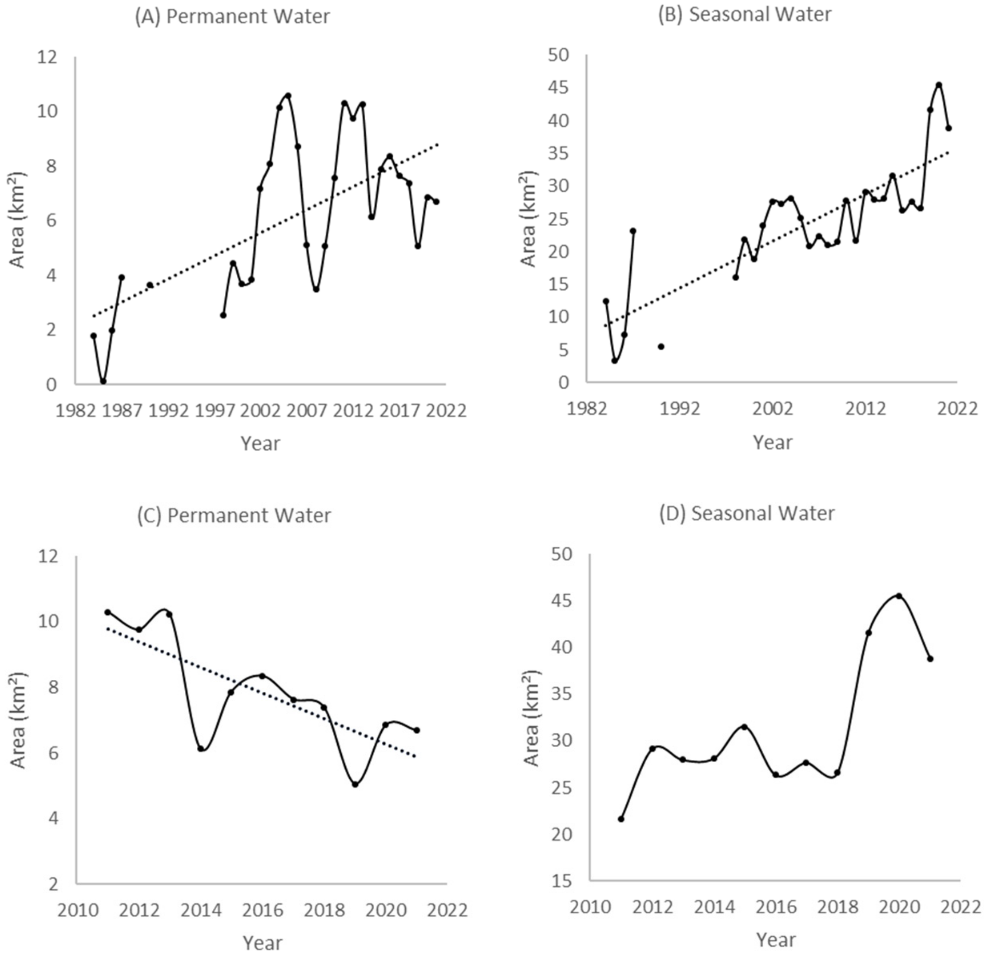

Figure 3. Permanent and seasonal water time series. Gaps from 1988, 1989, 1991 to 1997, when images were not available. Time series presents a normal distribution according to the Shapiro–Wilk test ($p > 0.05$). (**A**,**B**) represent an increasing trend in permanent and seasonal water surface area between 1984 and 2021. (**C**) indicates a decreasing trend in permanent water surface area in the most recent years from 2010 to 2021. (**D**) exhibits the seasonal water surface area between 2011 and 2021, without indicating trends.

On the other hand, a statistically significant decreasing trend (S = −35 [dimensionless], $p < 0.05$) was verified in permanent water surface area between the years 2011 to 2021 (Figure 3C). Taking into account that the construction of the latest major reservoir was the Solea dam in 2010 [47], it can be concluded that there was no expansion of the water surface resulting from engineering projects since then. In the same period, there is no statistically significant trend (S = 21, $p > 0.05$), according to the Mann–Kendall trend test for the seasonal water area time series (Figure 3D).

Cyprus reservoirs exhibit high storage variability, which is reflected in the water's surface area throughout the year. The construction of the five major reservoirs (Table 1) was undertaken to harness the flow of rivers originating from the mountainous Troodos region. However, only a fraction of these reservoirs maintain water levels consistently throughout the entire historical record (Figure 4). Some natural water bodies completely dry out in certain periods, as is the case with the Main Salt Lake. The full list of Cyprus reservoirs and the main contributions to total storage can be found in Appendix A, respectively Table A1 and Figure A1.

Table 1. Characteristics of the five large reservoirs in Cyprus.

Name	Year	River	Height (m)	Capacity (m^3)	Lat	Long
Kouris	1988	Kouris	110	115,000,000	34.85	33.36
Asprokremmos	1982	Xeros Potamos	53	52,375,000	34.73	32.56
Evretou	1986	Stavros tis Psokas	70	24,000,000	34.96	32.47
Kannaviou	2005	Ezousa	75	18,000,000	34.93	32.59
Kalavasos	1985	Vasilikos	60	17,100,000	34.81	33.26
Dipotamos	1985	Pentaschoinos	60	15,500,000	34.89	33.62

Source: Produced with data available from WDD [48].

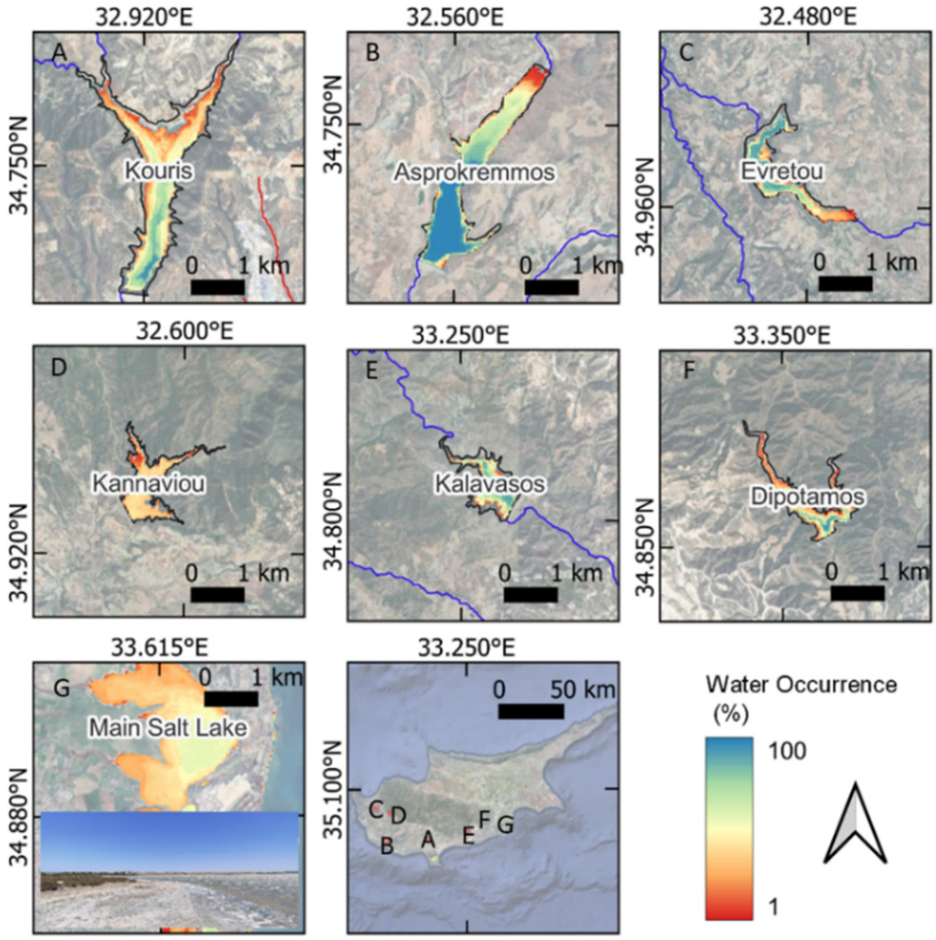

Figure 4. Water occurrence for the entire time series (1984–2021). The occurrence of water reaching a hundred percent indicates that every single-pixel observation recorded water on all available images.

Analyzing the largest reservoir in Cyprus reveals a consistent decline in water storage in recent years. This decline is evident in Kouris dam, identified as ID 174665 in the Global Lake Evaporation Volume and Surface Area dataset (Figure 5A) and ID 4468 in the Global Reservoir Storage dataset (Figure 5B). Both sources exhibit a statistically significant decreasing trend ($p < 0.05$) between 2011 and 2018 (the final year of available data), indicating a trend of depletion and insufficient recovery of reservoir levels.

When studying climate events that impact water availability, we need to study the periodicity of these events so that we are prepared for the future. In this sense, three signals with periods at approximately 6, 8, and 11 years were observed for permanent water (1984–2021) (Figure 6A), with a strong signal throughout the series (Figure 6C), as well as 6 and 8 years for seasonal water (Figure 6B,D).

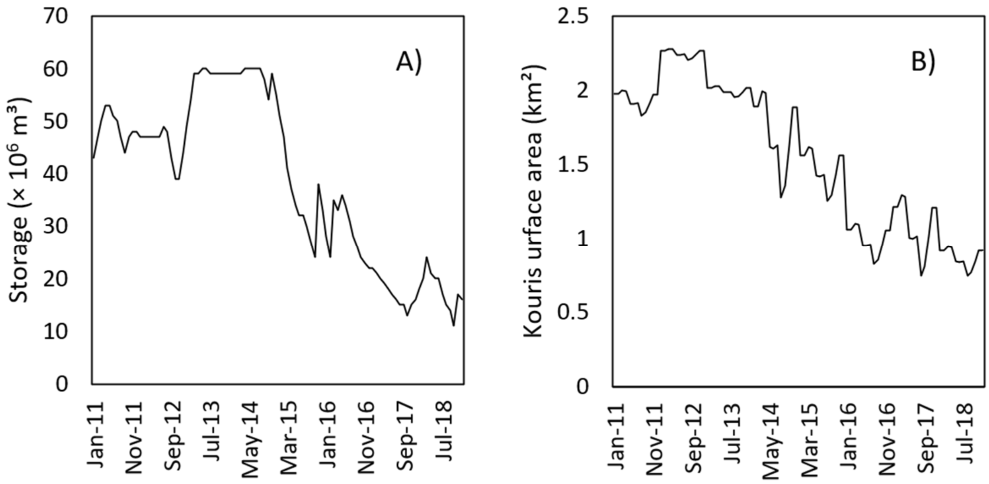

Figure 5. Kouris reservoir. (**A**) Global Reservoir Storage dataset [39]. (**B**) Global Lake Evaporation Volume dataset and surface area [38]. Tabular data were obtained from the cited database, the ID code to the Kouris dam are, ID 4468 and ID174665, respectively.

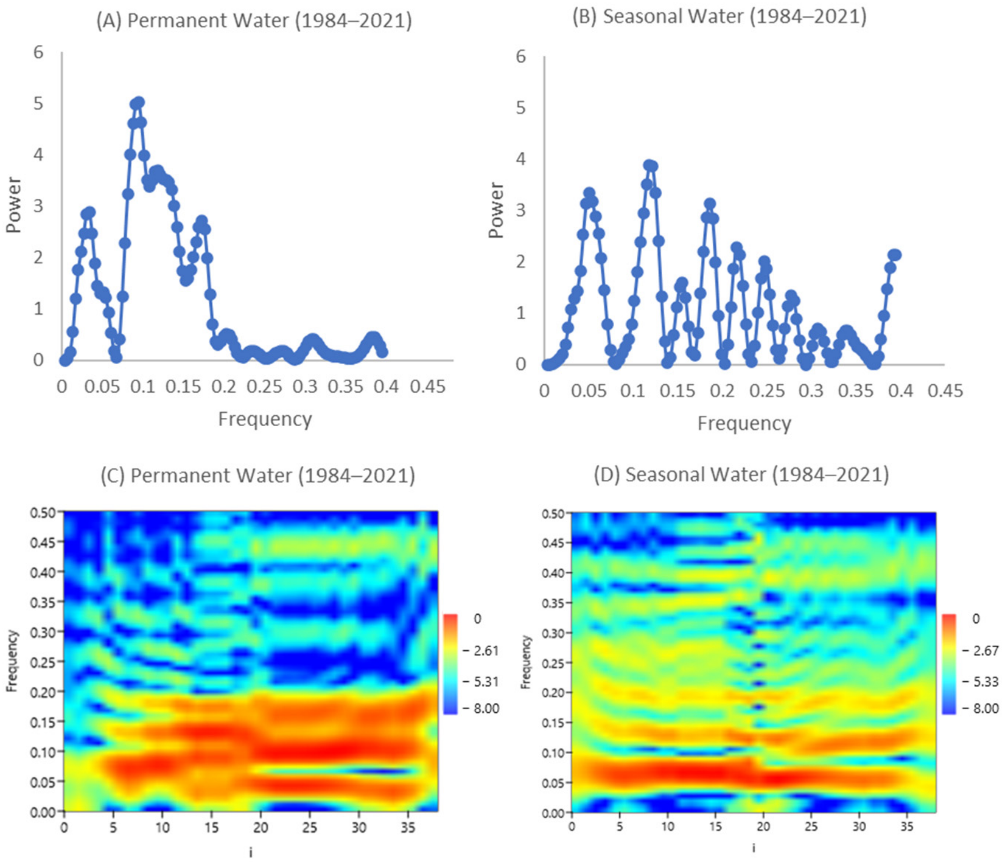

Figure 6. Periodograms power spectral density: (**A**) permanent water (1984–2021); (**B**) seasonal water (1984–2021). Spectral analysis by Evolutive Fourier transform, sample position is shown on the x axis, frequency (in periods per sample) on the y axis, and power on a logarithmic scale as color scale: (**C**) permanent water (1984–2021); (**D**) seasonal water (1984–2021).

Analyzing the inflow and storage based on measured data (Figure 7), we can identify one of the lowest inflows at the beginning of the historical series in 1990–1991. Six years later, another period of low inflow was recorded, with a minimum in 1996–1997. Eight years after that, another period of low inflow can be observed, starting in 2004–2005 and ending in 2007–2008, and the latter marks 11 years after 1996–1997. From 2007–2008 onwards, another period of very low inflow is recorded in 2013–2014, and another in 2015–2016, exactly six and eight years, respectively, after the previous occurrence. The most recent minimum inflow occurred in 2020–2021, eight years after the minimum in 2013–2014. As expected, the reservoir storage shows a delay (lag) between the reduction in inflow and the decrease in reservoir level (Figure 7). The observed inflow data validate our remote sensing approach coupled with frequency analysis, underscoring the strong agreement between various data sources.

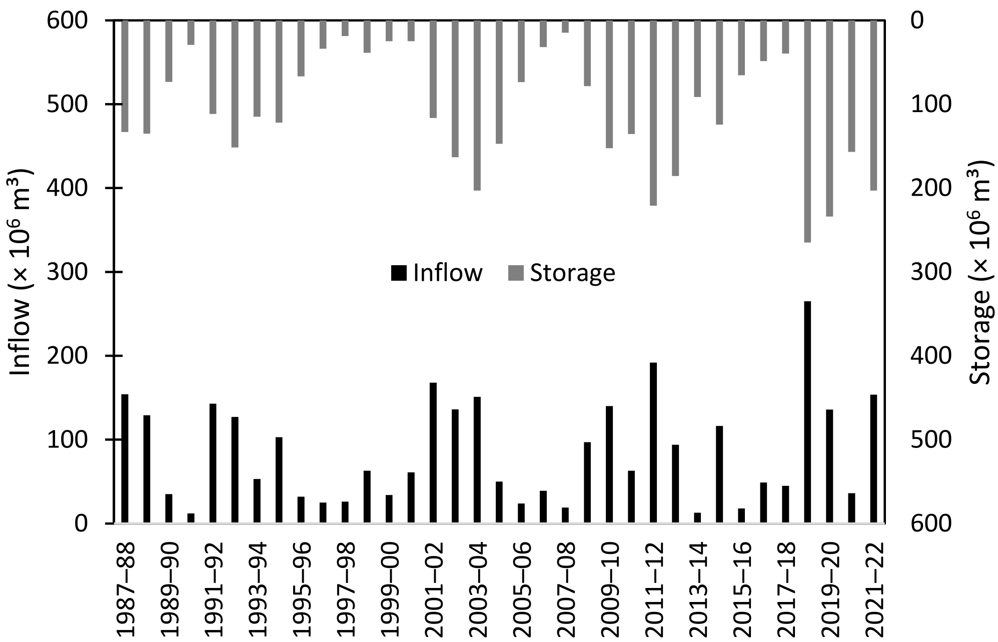

Figure 7. Water inflow and water storage in Cyprus reservoirs. Figure produced with data available on WDD [49].

Water reservoirs depend on the precipitation regime, in this sense the climatological norm of precipitation in Cyprus has been systematically decreasing with each update since the beginning of the 20th century (Figure 8). It has decreased from 559 mm annually to 476 mm, a decrease of 18% over the entire observed historical series. Furthermore, an increase in the frequency of years with precipitation below the climatological average can be observed. Since the 1990s, more than half of the years have been classified with below-average climatological precipitation, as well as drought and severe drought events (Figure 8).

Water availability has a huge impact on vegetation. In that regard, the Evretou river basin presents interesting features for analysis, as approximately half of the region consists of preserved forested areas, while the remaining portion is devoted to irrigated agriculture. The Evretou watershed exhibits an increasing trend on mean NDVI values from 1984 to 2021 (Figure 9A), which is linked to the expansion of irrigated areas in the region, as well as afforestation efforts in the higher regions of the basin.

On the other hand, when examining areas classified as rainfed agriculture according to the global land cover product from the European Space Agency, we observed mean NDVI values around 0.21, characterizing a much more arid region than the Evretou basin, whose average NDVI value was 0.33. This result shows the impact of water scarcity on rainfed agriculture. Furthermore, a greater amplitude in the range of maximum NDVI values (Figure 9B) was observed, along with a statistically significant decreasing trend ($p < 0.05$)

for the minimum NDVI values, which indicates that dry periods have been intensifying in recent decades with severe impacts on vegetation.

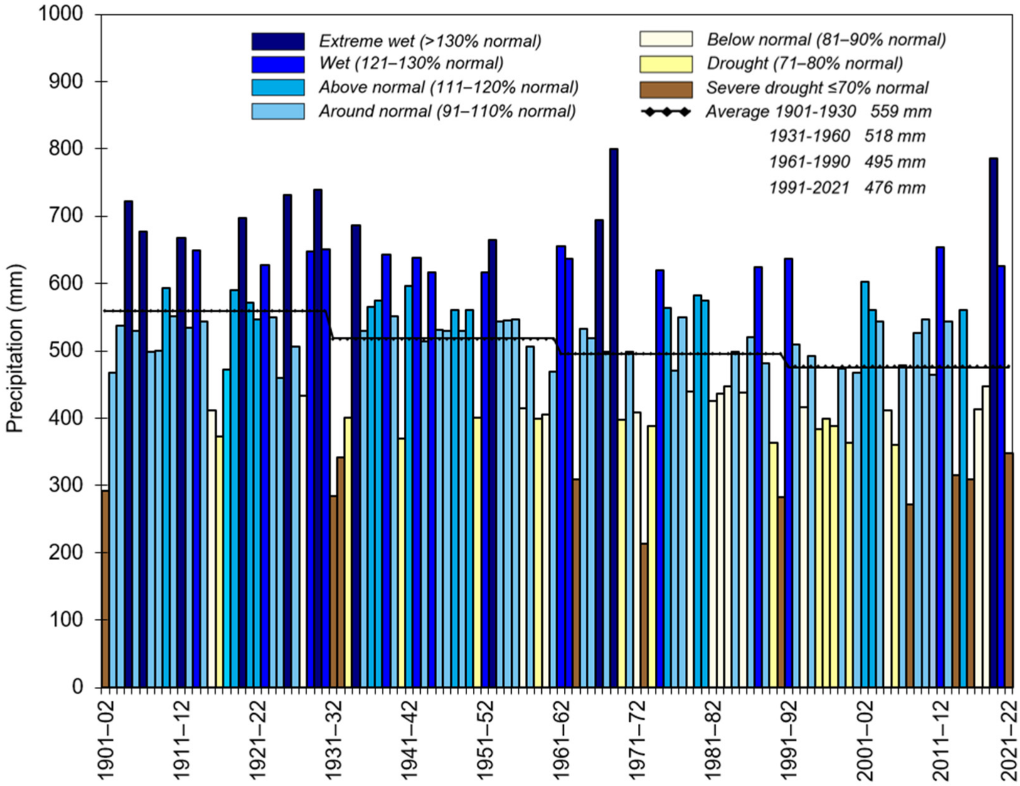

Figure 8. Annual precipitation. The division of years into dry, normal and wet years are based on annual rainfall percentual deviation of the climatological mean (30 years period) as obtained from WDD [50].

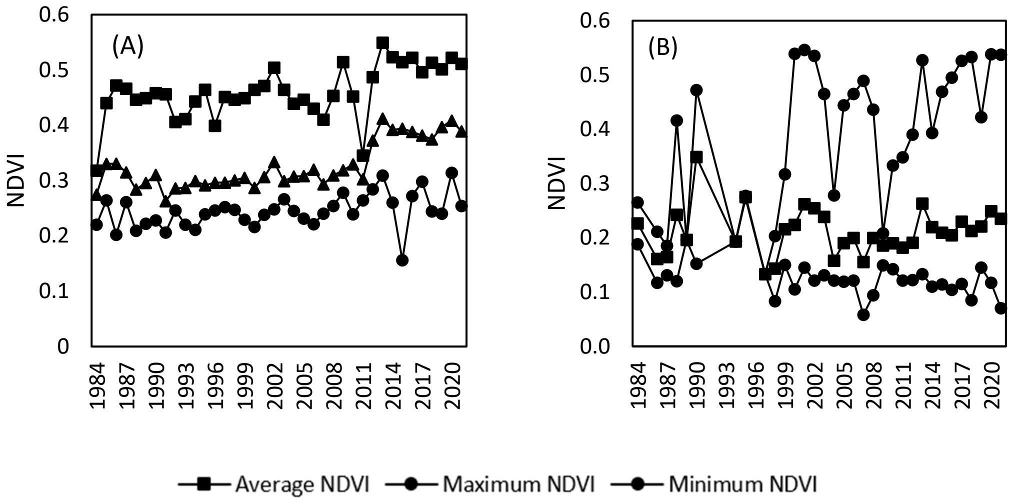

Figure 9. Normalized Difference Vegetation Index (NDVI). (**A**) Evretou watershed dominated by forest and irrigated crops. (**B**) Rainfed agriculture areas from global land cover/European Space Agency.

In the last decade (2010–2021), the minimum NDVI values for rain-fed agriculture show a high correlation with the observed reduction in precipitation in the region, with a Pearson correlation coefficient of 0.67 ($p < 0.05$). This result was expected for non-irrigated regions, considering that the decrease in water availability directly impacts NDVI. On the other hand, a cross-correlation analysis revealed a negative correlation of $r = -0.66$ ($p < 0.05$)

between the water surface area and the average NDVI values in the Evretou basin. This indicates that for the irrigated agriculture region, the increase in NDVI values is directly related to the decrease in the water surface area of the reservoirs, meaning that irrigation has been maintained at unsustainable levels in recent years. Similarly, the cross-correlation analysis indicates a negative correlation of $r = -0.66$ ($p < 0.05$) with a lag of 1 year, as well as $r = -0.80$ with a lag of 6 years, which reveals an impact in the following years.

4. Discussion

One of the worst recent water crises faced by Cyprus began in 2006. During this period, an agreement was reached for the transfer of 8 million cubic meters of water from Greece to Cyprus in 2008, with a transportation cost of EUR 35 million [22]. After that, the lowest inflows to the reservoirs were recorded in 2014 and 2016 (Figure 7), which corresponds to 6 and 8 years, respectively, from 2008; and 11 years from 2004–2005. This is in perfect agreement with our results (Figure 3), where we have identified recurrency cycles of approximately 6, 8, and 11 (Figure 6).

Also, the observed decrease in precipitation (18% over the past century—Figure 8) aligns with the literature [51], which describes changes in rainfall patterns in the Euro-Mediterranean region over the course of the 20th century. Therefore, the water surface area variation (Figure 3) is due a combination of climatic issues [8,9] with usage demands [52]. Regarding water uses, residential water supply and tourism account for approximately 30% and 5% of the island's water demand, respectively. Since 1984, the population of Cyprus has grown by approximately 80%, reaching 918,100 individuals in 2021 [53]. Furthermore, Cyprus receives on average, four times its population in the number of tourists distributed throughout the year.

In order to improve water availability, the Department of Forestry in Cyprus has been actively involved in reforestation efforts, primarily focusing on revitalizing neglected agricultural lands and areas affected by wildfires [54]. While studying a region in Paphos, adjacent to the Evretou watershed, Andronis et al. (2022) identified a decreasing trend in NDVI values between 2013 and 2018, highly correlated with the rise in surface temperature during the same period [55]. Comparing our results for the Evretou watershed during the same period (Figure 9), we also observed a statistically significant downward trend in mean NDVI values ($p < 0.05$), consistent with their results [55]. This negative trend in the analyzed period is attributed to the precipitation regime, with the years 2014 and 2016 being classified as extremely dry, followed by two years of below-average precipitation in 2017 and 2018 (Figure 4).

Engineering projects have also been employed to enhance water availability, desalination has constituted one key element to address water demand. Starting from the late 1990s, desalinated water of different sources has contributed to increasing water availability [56]. Even so, in Cyprus, large reservoirs are struggling to maintain their minimum levels (Figure 4), as also observed in other reservoirs globally [39]. For example, the Kouris dam (Figure 5), the largest in Cyprus, inaugurated in 1988, had a predicted initial annual mean inflow of 46.3 (Mm^3), but data observed between 1971–2000 indicated an average input of 30 Mm^3, a reduction of 35%. The same can be observed for many other dams, as shown by a report published from the FAO [57].

Simulations were performed to evaluate future trends in the water resources of Cyprus by focusing on water flux changes in the Kouris catchment, and showed that the present mean annual rainfall can drop between 7% and 25%, for the mild and extreme scenarios of climate changes, RCP2.6 and RCP8.5, respectively [58]. Simulations for the Asprokemos and Kouris dams indicated a water storage decrease, and more severe drought events are expected in the future [59]. In addition, the quality of the water, with constituents such as nitrate, can impose restrictions on the use of water [60,61].

Some authors assert that the water shortage in Cyprus has become a notable concern in recent decades due to prolonged periods of drought and insufficient management actions [17]. Likewise, the academic community has been increasingly discussing flash droughts. Unlike conventional, gradually progressing droughts, flash droughts emerge suddenly and deplete water resources swiftly. This rapid onset can disrupt both ecological and agricultural systems, creating imbalances [62].

When surface water is not available, the over-pumping of groundwater has critical consequences, causing the irreversible depletion of underground aquifers and, in the case of coastal aquifers, their non-reversible salinization [63–65]. Groundwater analysis in Cyprus identified sodium, chloride, and sulphate as the dominant ions, with water quality assessments indicating potential restrictions for irrigation purposes due to high salt levels [21]. The Morphou aquifer, the largest coastal aquifer in northwestern Cyprus, exhibits water quality that falls below the acceptable limits set by the World Health Organization in terms of chloride and other chemical parameters [66,67]. In order to tackle the task of balancing water supply and demand, effective water management plays a vital role, aiming to ultimately achieve water security. Generally, water use priorities are not fully understood by decision makers, as well as the risks related to climate change and seasonal variability [68].

Water management involves a range of strategies and measures, such as implementing water conservation practices, adopting efficient irrigation techniques, promoting wastewater treatment and reuse, implementing watershed management plans, and practicing integrated water resources management [16,17,58,69]. These approaches aim to optimize water allocation, improve water use efficiency, and mitigate the risks associated with water scarcity and water-related disasters.

In this way, the River Basin Management Plan is a tool that sets priorities for water use and outlines the actions that should be implemented to ensure both the quantity and quality of water [29]. However, the political conflict in Cyprus is a challenge to be faced [70], mainly on groundwater uses, since water management is not carried out in an integrated manner between the occupied northern part of the island and the Republic of Cyprus.

Determining water scarcity involves evaluating the demand for a specific quality of water and its availability [71]. By considering the availability and demand for water, it becomes feasible to conduct a water balance assessment. In the Republic of Cyprus, the water balance was positive, for the year 2021, allowing accumulation in the reservoirs. However, in the years 2013, 2014, and 2017, the water balance was negative [63], in these cases, there was an overexploitation of underground reserves. It was estimated that the annual water demand in the occupied northern part of Cyprus, primarily driven by agricultural use (80%), exceeded the available supply by up to one-third, before the water pipeline constructed between Turkey and the island [72].

If there is not enough water for irrigation, agricultural activity may become unviable. In this context, it is important to evaluate the suitability of this sector on the island. Given that the agricultural sector is the primary water consumer, implementing precision agriculture techniques is crucial [21]. Similarly, other alternatives should be explored, such as wastewater recovery for irrigation [73].

Some other measures can be implemented to enhance water availability. These include the installation of rainwater collection systems for domestic purposes, the implementation of wastewater recycling initiatives and the expansion of desalination plants. Also, the utilization of renewable energy as a power source for seawater and brackish desalination presents an environmentally viable solution to address the increasing global demand for freshwater while mitigating the adverse effects associated with fossil fuel consumption [74]. Likewise, strategies to decrease water demand include educational campaigns, conservation efforts, and the strategic allocation of new water users [14].

5. Conclusions

Due to the construction of many water reservoirs in Cyprus, a statistically significant increasing trend ($p < 0.05$) has been observed for the water surface area in the last almost four decades, enabling the social and economic development of the region. Conversely, after the construction of the last reservoir, Solea dam in 2010, a statistically significant decreasing trend ($p < 0.05$) was verified in the permanent water surface area, which indicates that in the near future there may be restrictions on water use in the region. Water surface variation is due to a combination of climatic issues and usage demands. Cycles of approximately 6, 8, and 11 years were observed for permanent water, which indicate recurrent cycles of water scarcity. Therefore, decision makers and the population must increasingly prepare for scarcity events.

The high amplitude in the range of maximum NDVI values along with a statistically significant decreasing trend ($p < 0.05$) for the minimum NDVI values has indicated that dry periods have been intensifying in recent decades. Therefore, strong impacts have already been observed on rainfed local agriculture, which needs to be discussed in terms of viability and continuity since its replacement by irrigated agriculture is responsible for a large demand for water, which is already scarce.

The techniques used in this work to construct time series together with trend analysis techniques provided a good analysis capacity, based on the convergence of different sources of information showing the reduction in local water availability. The methodology can easily be replicated elsewhere since the use of remote sensing products allows the study of regions without relying on government databases.

Future studies may focus on a more detailed analysis of regions with irrigated agriculture and their relationship with water reservoirs, as well as in rain-fed agriculture areas and their connection to groundwater use, using available site-specific data for validation. To enhance the discussion on the impacts of water scarcity on agriculture, a more refined temporal series of land use and cover in combination with local agricultural production data can be valuable, if available. Additionally, new studies should focus on potential strategies to enhance water resources in the region or actions aimed at adapting to climate change.

Finally, Cyprus can be considered a valuable case for managing water scarcity, anticipating problems and solutions to be faced in many places around the world.

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Appendix A

Table A1. Full list of Cyprus reservoirs.

Name	Year	River	Height (m)	Capacity (m^3)
Kouklia	1900	-	6	4,545,000
Lythrodonta (Lower)	1945	Koutsos (Gialias)	11	32,000
Kalo Chorio (Klirou)	1947	Akaki (Serrachis)	9	82,000
Akrounta	1947	Germasogeia	7	23,000
Galini	1947	Kampos	11	23,000
Petra	1948	Atsas	9	32,000
Petra	1951	Atsas	9	23,000

Table A1. *Cont.*

Name	Year	River	Height (m)	Capacity (m^3)
Lythrodonta (Upper)	1952	Koutsos (Gialias)	10	32,000
Kafizis	1953	Xeros (Morfou)	23	113,000
Agios Loukas	1955	-	3	455,000
Gypsou	1955	-	3	100,000
Pera Pedi	1956		22	55,000
Kantou	1956	Tabakhana (Kouris)	15	34,000
Pyrgos	1957	Katouris	22	285,000
Trimiklini	1958	Kouris	33	340,000
Morfou	1962	Serrachis	13	1,879,000
Kioneli	1962	Almyros (Pediaios)	15	1,045,000
Athalassa	1962	Kalogyros(Pediaios)	18	791,000
Lefka	1962	Setrachos(Marathasa)	35	368,000
Prodromos Reservoir	1962	Off - stream	10	122,000
Ag.Georgios—(Recharge)	1962	-	6	90,000
Sotira—(Recharge)	1962	-	8	45,000
Panagia/Ammochostou	1962	-	7	45,000
KanliKiogiou	1963	Ghinar (Pediaios)	19	1,113,000
Ammochostou—(Recharge)	1963	-	8	165,000
Paralimni—(Recharge)	1963	-	5	115,000
Agia Napa—(Recharge)	1963	-	8	55,000
Ammochostou—(Antiflood)	1963	-	5	50,000
Ag. Loukas Lake—(Recharge)	1964	-	3	4,545,000
Kiti	1964	Tremithos	22	1,614,000
Agios Nikolaos—(Recharge)	1964	-	2	1,365,000
Paralimni Lake—(Recharge)	1964	-	1	1,365,000
Argaka	1964	Makounta	41	990,000
Ovgos	1964	Ovgos	16	845,000
Mia Milia	1964	Simeas	22	355,000
Liopetri	1964	Potamos	18	340,000
Frenaros—(Recharge)	1964	-	5	115,000
Agros	1964	Limnatis	26	99,000
Deryineia—(Recharge)	1964	-	6	23,000
Polemidia	1965	Garyllis	45	3,400,000
Agia Marina	1965	Xeros	33	298,000
Mavrokolympos	1966	Mavrokolympos	45	2,180,000
Pomos	1966	Livadi	38	860,000
Kalopanagiotis	1966	Setrachos (Marathasa)	40	363,000
Makrasyka—(Recharge)	1966	-	8	195,000
Xylofagou—(Recharge)	1966	-	7	86,000
Kontea—(Recharge)	1966	-	5	82,000

Table A1. *Cont.*

Name	Year	River	Height (m)	Capacity (m^3)
Avgorou—(Recharge)	1966	-	3	68,000
Frenaros—(Recharge)	1966	-	7	45,000
Sotira—(Recharge)	1966	-	5	32,000
Achna Mesania—(Recharge)	1967	-	4	90,000
Lysi—(Recharge)	1967	-	7	77,000
Agios Georgios—(Recharge)	1967	-	3	68,000
Germasogeia	1968	Germasogeia	49	13,500,000
Sygkrasis	1968	Merikeros	7	1,115,000
Ormideia—(Recharge)	1968	-	5	100,000
Akanthou—(Recharge)	1968	-	6	45,000
Agios Epiktitos—(Recharge)	1968	-	6	34,000
Vrysoulles—(Recharge)	1969	-	7	140,000
Morfou—(Recharge)	1969	-	5	130,000
Xylotymvou—(Recharge)	1969	-	7	50,000
Protopapades—(Recharge)	1970	-	6	90,000
Lefkara	1973	Syrgatis (Pentaschoinos)	71	13,850,000
Masari—(Recharge)	1973	Serrachis	15	2,273,000
Palaichori—Kampi	1973	Akaki (Serrachis)	33	620,000
Kyperounta No 1 *	1974	Off-stream	7	50,000
Arakapas	1975	Germasogeia	23	129,000
Lympia (new)	1977	Tremithos	12	220,000
Pelendri *	1980	Off-stream	18	123,000
Eptagoneia No 1 *	1980	Off-stream	16	92,000
Chandria *	1980	Off-stream	35	70,000
Melini *	1980	Off-stream	22	59,000
Agioi Vavatsinias No 1 *	1980	Off-stream	17	55,000
Akapnou—Eptagoneia *	1981	Off-stream	9	132,000
Kato Mylos *	1981	Off-stream	23	104,000
Eptagoneia No 3 *	1981	Off-stream	12	65,000
Agioi Vavatsinias	1981	Vasilikos	19	53,000
Asprokremmos	1982	Xeros Potamos	53	52,375,000
Xyliatos	1982	Lagoudera (Elia)	42	1,430,000
Arakapas No 1 *	1982	Off-stream	12	192,000
Eptagoneia No 2 *	1982	Off-stream	8	127,000
Kyperounta No 2 *	1983	Off-stream	27	273,000
Lagoudera *	1983	Off-stream	36	71,000
Ora *	1983	Off-stream	18	62,000
Agridia *	1983	Off-stream	18	59,000
Choirokoitia *	1984	Off-stream	16	205,000
Dierona *	1984	Off-stream	24	159,000

Table A1. *Cont.*

Name	Year	River	Height (m)	Capacity (m^3)
Arakapas No 2 *	1984	Off-stream	12	120,000
Farmakas No 2 *	1984	Off-stream	24	61,000
Agioi Vavatsinias No 2 *	1984	Off-stream	25	43,000
Farmakas No 1 *	1984	Off-stream	18	21,000
Kalavasos	1985	Vasilikos	60	17,100,000
Dipotamos	1985	Pentaschoinos	60	15,500,000
Esso Galata *	1985	Off-stream	27	35,000
Evretou	1986	Stavros tis Psokas	70	24,000,000
Achna	1987	Off-stream	16	6,800,000
Aradippou	1987	Parthenitis	14	90,000
Kouris	1988	Kouris	110	115,000,000
Vyzakia	1994	Off-stream	37	1,690,000
Melini No 2 *	1996	Off-stream	36	97,000
Odou No 2 *	1996	Off-stream	34	53,000
Odou No 1 *	1996	Off-stream	33	32,000
Arminou	1998	Diarizos	45	4,300,000
Tsakistra	2000	Limnitis	23	100,000
Tamassos	2002	Pediaios	34	2,800,000
Kannaviou	2005	Ezousa	75	18,000,000
Klirou-Malounta-Akaki	2007	Akaki (Serrachis)	38	2,000,000
Solea	2010	Off-stream	56	4,500,000

* Ponds with membrane lining (height 10 m). Source: Produced with data available from WDD [48].

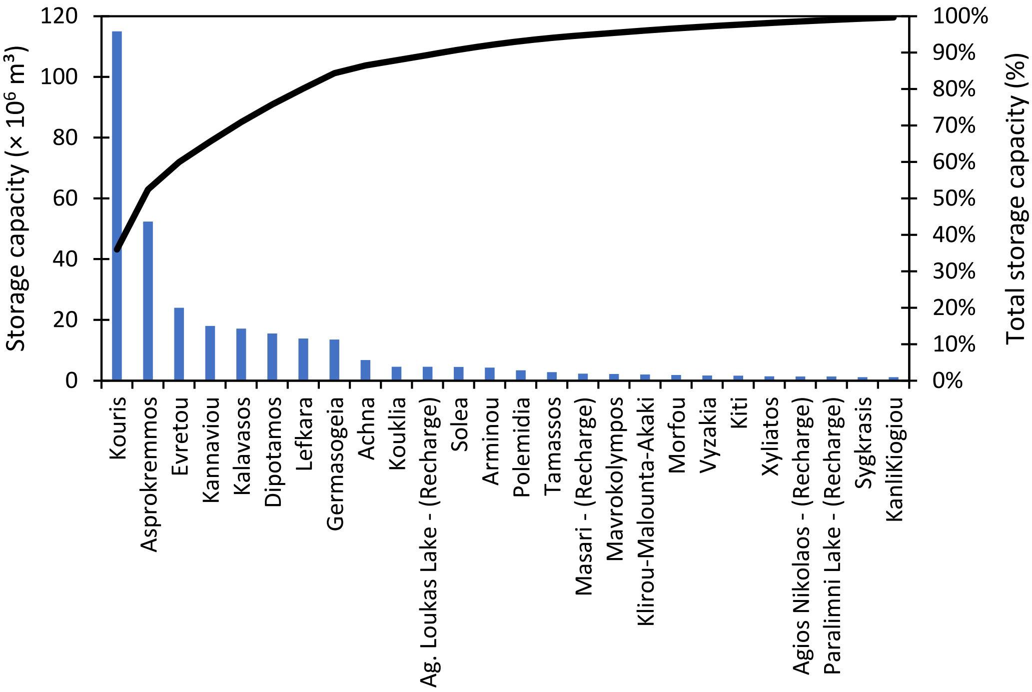

Figure A1. Main reservoirs contributing to total storage.

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