Master’s degree program in Territorial, Urban, Environmental and Landscape Planning
Curriculum: Planning for the Global Urban Agenda

Master’s Thesis

Innovative models for sustainable water management by rainwater harvesting in ancient reproposed tanks in Ventotene (LT)

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Abstract

Shortage of water is a growing global concern, particularly evident in island and desert regions where conventional water sources are likely to be low and vulnerable to the impacts of climate change. In this dissertation, such a vital problem is addressed through the presentation and examination of innovative models of sustainable water management through strategic implementation of rainwater harvesting in rehabilitated ancient tanks with particular reference to Ventotene island (LT), Italy. The research points out the tremendous possibility to integrate centuries-old water management expertise with present-day sustainable methods to provide resilience and self-sufficiency in water-poor communities.

The research initially establishes the overarching importance of sustainable water management in modern geopolitics and climate, emphasizing the need for decentralized and resilient water supply systems. It then delves into Ventotene's unique geographical, historical, and geological context. This chapter highlights the island's intrinsic vulnerability to drought on the basis of its small land mass, geology, and growing tourist pressures, and complemented by its magnificent history of sophisticated ancient waterworks, including an extensive network of hidden cisterns and tanks. These ancient structures, originally designed to catch rainwater, are a valuable, but at present underutilized, asset for modern water security.

The underlying nature of this work is the engineering and analysis of new designs for the restoration and functional rehabilitation of such old tanks for application in contemporary rainwater harvesting. It goes beyond historical context into the engineering, hydrologic, and socio-economic feasibility of their incorporation within an overall, island-wide water management strategy. Due attention is given to taking into consideration factors such as water quality problems, appropriate filtration and treatment technologies suitable for non-potable and potentially potable uses, and the most optimal design of collection and distribution systems to ensure maximum efficiency and minimum environmental impact.

Moreover, this thesis explores the potential use of these models not only for augmenting water supply, but also for overall environmental and urban development objectives. By reducing reliance on external water imports, these systems can reduce energy consumption with respect to desalination or transport, hence lowering the carbon footprint of the island.

The findings of the present research provide a solid support system for policymakers, planners, and community residents in Ventotene and other similar insular settings to implement effective and sustainable rainwater harvesting measures. It offers practical examination of the technical specifications, economic viability, and regulatory compliance involved in effective project implementation. The visionary models presented below are a testament to the eternality of ancient wisdom in building a sustainable future.

Keywords: Stormwater management, reservoir, water storage

Contents

Glossary terms

Storm Water Management Modelling	SMM
Geographic Information System	GIS
Rainwater harvesting	RWH
Design Rainfall	DR
Recorded Rainfall	RR
Sustainable Development Goals	SDGs
Low Impact Development	LID
Digital Terrain Model	DTM
Open-Source Map	OSM
Sustainable Urban Drainage Systems	SuDS
Stormwater Control Measures	SCMs
Litre Per Second LPS Water Elevation Profile	LSP
Hectares	Ha
Square metre	M2

Chapter 1.

Introduction

The first chapter of the thesis provides a detailed explanation of the conditions that led the Ventotene Island, a tiny island in the Tyrrhenian Sea, to adopt sustainable water management. This chapter begins by explaining the importance of sustainable water management in the situation of small islands, where there is little freshwater and environmental vulnerability is a fact. A geographical, historical and geological background description is presented, which supports the need to know the special issues and dangers of stormwater management on the island.

The imperative role of stormwater management in reversing the harmful impacts of climate change on the environment and humankind is highlighted. As urbanization continues, there is an urgent need to enhance more creative and sustainable ways of dealing with expanding amounts of stormwater runoff, particularly through strategies such as rainwater harvesting.

Sustainable water management practice offers a promising solution through the integration of modern water systems and natural based solutions with urban infrastructures, hence fostering resilience and sustainability.

1.1. Importance of sustainable water management

Sustainable water management (SWM) is the pillar of sustainable development, where there exists equilibrium in meeting the demands of the current and future generations (Bozorg-Haddad et al., 2021). SWM addresses the most demanding issues for both the developing and developed nations, such as water scarcity, quality degradation, and competing demands by sectors (Khadse et al., 2012; Russo et al., 2014). An integrated approach to SWM recognizes all forms of water as resources available for utilization, with an aim to improve agricultural water productivity in ensuring global food security needs (Russo et al., 2014). The importance of sustainable water management is even more apparent for small islands, where freshwater availability and environmental susceptibility are enormous challenges due to limited water resources.

Effective SWM strategies include recycling, water reuse, and affordable policies that guarantee sustainability in both socioeconomic and environmental aspects (Bozorg-Haddad et al., 2021). Fifty percent of the global population experiences an acute water shortage every year (Li et al., 2024), a condition that requires urgent remediation. SWM objectives can only be achieved through an integrated effort involving policy innovation, technology, behavior change, and global collaboration, supplemented by local interventions (Li et al., 2024). One of the measures under SWM is stormwater treatment and reuse, which is crucial. In particular, through rainwater harvesting and utilization, communities can reduce their dependence on off-site water supplies, diminish the impact of drought, and enhance water security. Rainwater refers to freshwater that falls directly as precipitation, whereas stormwater is the portion of rainwater that flows over the ground surface. Rainwater is typically regarded as cleaner, as it is often collected directly from rooftops before coming into contact with other surfaces. In contrast, stormwater tends to accumulate various pollutants as it travels across impervious and potentially contaminated surfaces such as roads, pavements, and soil.

1.2. Rainwater harvesting in repurposed ancient tanks and its role in water sustainability.

Rainwater harvesting (RWH) has been practiced for centuries, particularly in arid and semi-arid regions around the Mediterranean and India (Mays, 2014; Akpinar Ferrand & Cecunjanin, 2014). Ancient civilizations constructed cisterns and tanks to store rainwater and aqueduct water, ensuring water sustainability during periods of scarcity (Mays, 2014). In Kerala, India, temple tanks serve not only as water harvesting systems but also as integral parts of community life (Maya, 2003). Despite their historical significance, many traditional RWH systems have fallen into disrepair due to increased reliance on groundwater (Meter et al., 2016).

Recent initiatives aim to revive these systems as a means of addressing water scarcity. Studies in India demonstrate that ancient RWH tanks significantly alter catchment water balances by reducing runoff and increasing groundwater recharge, while tanks currently meet approximately 40% of crop water requirements. (Van Meter et al., 2016). However, an improved management could enhance their efficiency further. Combining modern water systems with traditional RWH methods presents a viable strategy for adapting to climate change in water-scarce regions (Akpinar Ferrand & Cecunjanin, 2014).

1.3. Geographical, historical and geological context of Ventotene (LT)

Ventotene, a small volcanic islet of Italian maritime jurisdiction, is located in the Tyrrhenian Sea, some distance off the coast of the border between Campania and Lazio (Figura 1); geographically, together with the Ponza, Palmarola, Zannone, Gavi and Santo Stefano islets, it forms part of the Pontine Islands, while from an administrative perspective it is part of the municipal district of Ventotene (LT) (Figure 2). It is mid-way between Ischia and Ponza and 25 nautical miles away from Gaeta and 19 nautical miles away from Ischia. The island is elongated from SW to NE with a length of maximum 2,900 m and in breadth of less than 800 m. It is elongated on a surface area of 1.54 km^2 (154 hectares) and is the smallest municipality in terms of surface area of central Italy. The islands of Ventotene and Santo Stefano are included in the State Nature Reserve, while the waters around the Ventotene and Santo Stefano islands are included in the Marine Protected Natural Area (MPA) "Isole di Ventotene e S. Stefano".

Ventotene is historically significant in particular for its strategic location in the Roman and Bourbonic periods. During Roman times, the island served both as a summer palace of the Emperor and as an exile home of political figures, proving to be strategic as well as secluded. The Romans also constructed elaborate water management systems in the form of rainwater cisterns to harvest and aqueducts, to fulfill the island's limited freshwater availability. During Bourbonic times, Ventotene was also a place of confinement. The Bourbon authorities also built infrastructure on the island, including rainwater harvesting systems, using also the Romans ruins, to serve the needs of the population (De Rossi, 2019). Today, Ventotene has gained much prominence, particularly within the context of European federalism (Sandu, 2020).

Under Fascism, the island was a prison complex where Altiero Spinelli drafted the manifesto that paved the way for European integration (Fabbrini, 2021). Spinelli was in turn influenced by British federalist writings, including those of Lord Lothian, which had been smuggled onto the island by Luigi Einaudi (Bosco, 1988). Plans are constantly in the works to transform the old prison into a European school, symbolizing the transformation of total institutions in the European Union (Fabbrini, 2021). Other than its political symbolic role, Ventotene is today the site of argument in terms of environmental care and sustainability. Current plans emphasize the necessity to preserve the island not only as a site of memory but also as an ongoing laboratory of sustainable development, particularly in terms of energy and water management (Capizzi et al., 2020). The tuff cliffs of Ventotene are geologically unstable to landslides and erosion, testing its stability (Figure 3). Recent integrated geological surveys and remote sensing techniques were employed in order to assess cliff stability, and to inform risk reduction measures (Ruberti et al., 2020).

Geological vulnerability is not Ventotene's sole vulnerability. The dependence of the island on imported freshwater and lack of permanent natural water resources highlight the need to implement adaptive measures. Traditional Mediterranean practices, such as the utilization of rainwater harvesting by cisterns and surface run-off systems, have been explored as viable solutions to this problem (Charlesworth et al., 2016). Current water supply infrastructure, a significant portion of which is incorporated within Ventotene's urban plan, is proof that past residents had long adapted to similar climatic and environmental limitations. Solutions for the rehabilitation and improvement of these systems in the present involve combining the past knowledge with current remote sensing and monitoring methods to enhance the island's capacity to handle its water resources sustainably (Capizzi et al., 2020; Charlesworth et al., 2016). Ventotene does not possess natural freshwater resources, and the water supply up to 2017 was through tanker ships. It was only in recent times that a desalination plant was installed to meet the water needs of the island. The island's reliance on tanker ships and desalination plants, nevertheless, renders the island extremely vulnerable to water scarcity as well as drought Further, desalination poses additional challenges, such as high energy consumption, which can increase greenhouse gas emissions due to its reliance on fossil fuels. Moreover, the lack of a good rainwater collection and management system makes the island extremely vulnerable to flooding and erosion especially during heavy weather conditions. This further complicates the environmental issues of the island, necessitating the urgent necessity of responding to the island by means of sustainable water management measures. Traditional rainwater collection systems in Ventotene, like reused Roman and Bourbonic cisterns, have long played a key role in collecting and conserving rainwater. These systems are now abandoned and therefore less capable of reacting to the modern water management needs of the island.

Increased climate fluctuation and increased demand necessitate innovative approaches to improve efficiency in water conservation and supply (Capizzi et al., 2023). Modern research demands that ancient infrastructure be integrated with contemporary water management technologies. This approach also aligns with broader sustainability interventions by ensuring that water resources support both local inhabitants and seasonal visitors on the island (Capizzi et al., 2023).

These multilateral factors place Ventotene in a geo-historical context, which makes it an ideal case study for elaborating on sustainable water management. Ventotene can render its water supply more robust while preserving its cultural heritage through remote sensing, climate forecasting, GIS mapping, and water treatment strategies.

The intersection between heritage conservation and environmental sustainability also emphasizes the need for integral environmental policies resolving both heritage and contemporary sustainable concerns. By balancing natural and anthropogenic risks, Ventotene is an example of where the blend of historical value with contemporary environmental resilience is possible (Capizzi et al., 2023).

Figure1. Ventotene Island in Italy (source: Capizzi et al., 2023)

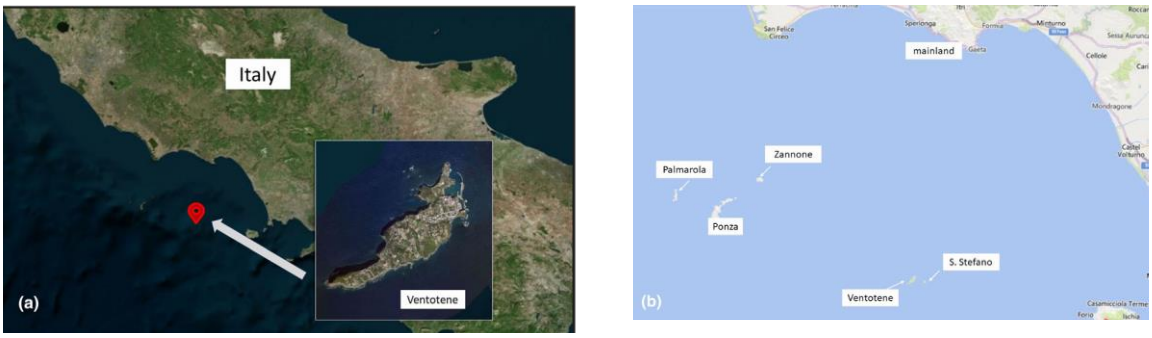

Figure 2. Ventotene Island in Italy (source: Capizzi et al., 2023)

Figure 3. Ventotene Island (source: STUDIO DI PREFATTIBILITÀ AMBIENTALE)

1.4. Project objectives

This thesis work is an outcome of an internship and thesis period conducted at ENEA. It is based on a project undertaken by the company within the framework of the Green Islands Programme, financed by the National Recovery and Resilience Plan (PNRR), with funds from the European Union Next Generation EU.

The primary objective of the project was to evaluate the potential use of existing old water reservoirs for rainwater recovery, which correlates with the United Nations' Sustainable Development Goals (SDGs) and promoting sustainable water management in the island. The feasibility of rainwater on building rooftops was evaluated. The collected rainwater can be potentially utilized for agricultural use and non-potable water for daily use. One of the island's old water reservoirs was selected as a case study. Simulations were performed to assess rainwater recovery from a municipal building according to both ancient circumstances and nowadays.

This objective fits within a broader vision of environmental and social resilience promoted by the Green Islands Programme. The reuse of ancient water infrastructures not only addresses practical challenges in water resource scarcity but also reflects a paradigm shift toward integrating cultural heritage into contemporary sustainability practices. This project seeks to demonstrate how the adaptive reuse of traditional systems—such as cisterns and rainwater tanks—can offer scalable models for other Mediterranean and insular contexts. Moreover, the project aligns with the European Union’s priorities under the PNRR framework to foster innovation while preserving ecological and historical values. By exploring the intersections of climate resilience, local knowledge, and digital tools such as GIS and hydrological simulation, the study contributes to the ongoing discourse on how small islands can pioneer low-impact, high-efficiency strategies in water management.
Data collection, as well as context, meteorological and spatial analysis were conducted through the internship program between June 2024 and October 2024. During the thesis period in 2025, evaluations were conducted on the selected case-study, studying the potential for rainwater recovery (Figure 4).
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The research was structured around a multi-faceted data collection and analysis approach.

First, during the internship, the integration of field surveys administered by ENEA, historical documentation, and spatial analysis tools was carried out to provide a comprehensive understanding of Ventotene’s rainwater recovery potential. More in detail, data for the project were collected using two approaches: field data gathered by the ENEA and official GIS data compiled by the student, which were later integrated. These datasets included detailed information mainly on water storage tanks, buildings, and surface areas.

- Field Surveys:

A detailed survey administered by ENEA of existing water storage infrastructures was analyzed to assess their current conditions, structural integrity, and historical modifications.
Direct observations conducted by speleologists and stakeholder interviews provided additional insights into the operational challenges and historical relevance of these reservoirs.

- Meteorological and geospatial Data Analysis:

Recorded rainfall data were collected and analysed to address the island's water supply challenges. High-resolution satellite imagery and official GIS datasets were utilized to analyse the spatial distribution of reservoirs and their connectivity with urban and agricultural zones. Building footprint data extracted from municipal CAD files enabled a precise calculation of available rooftop areas for rainwater harvesting potential. The spatial relationship between reservoirs, built environments, and topographical features was analysed to identify potential issues for integrating traditional storage systems with modern water infrastructure.

- Rainwater recovery potential

The rainwater recovery potential from the building roof of Ventotene island was assessed, considering local climatic conditions, historical precipitation data, and the structural characteristics of the roof. This evaluation aimed to estimate the volume of rainwater that could be collected and utilized, contributing to sustainable water resource management on the island.

During the thesis period subsequent analyses on a specific case-study were performed using the Storm Water Management Model (SWMM) software to assess the volume of collected water and the efficiency of the water collection network. Simulations were conducted to evaluate the potential for rainwater recovery from a municipal building, taking into account both historical and contemporary contexts. By simulating different scenarios, the study aimed to assess the efficiency, feasibility, and sustainability of rainwater harvesting in both past and present conditions, providing valuable insights for future water resource management strategies.

In conclusion, the thesis revealed that the ancient reservoirs in Ventotene, despite some structural deterioration, hold significant potential for integration into modern water management strategies. The spatial data integration allowed for the identification of priority areas where restoration efforts could have the highest impact.

By employing a combination of traditional knowledge and modern analytical tools, the study underscores the importance of preserving and repurposing historical water infrastructures as a sustainable solution for small islands facing climate change-related water scarcity.

Additionally, the project seeks to repurpose ancient heritage by incorporating modern water storage systems into existing structures. The initiative aims to develop effective interventions within urban environments, leveraging nature-based solutions and green infrastructure to enhance resilience against climate change. Through this research, the project aims to contribute valuable insights into sustainable water management practices, offering practical solutions for similar contexts worldwide

Moreover, the project clearly shows socio-economic benefits for small island communities, like Ventotene, integrating traditional water management with the modern framework. In minimizing dependence on external waters, the initiative will lower operational costs for municipalities and serve to strengthen local agriculture, thereby contributing to economic resilience. The preservation of ancient reservoirs as functioning infrastructure also encourages cultural heritage tourism, which is a possible additional revenue stream for the island. This dualism addresses sustainability as well as economic development, thus making the project replicable in other regions-it would also have broader policy frameworks regarding water scarcity in the context of climate change.

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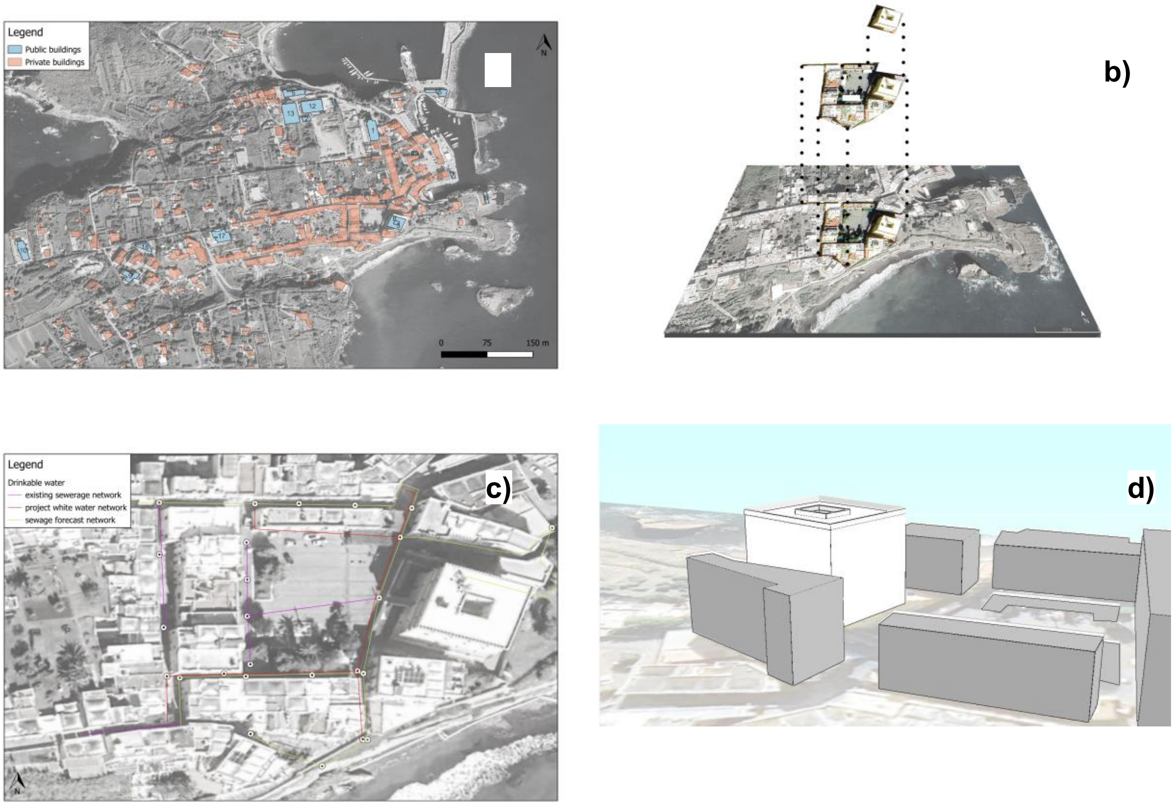

Figure 4. Summary of participation in the project (source: author). a) GIS datasets; b & c) case study; case study; d) SWMM simulation;

Chapter 2.

Literature Review

2.1. Overview of Rainwater Harvesting Systems

Rainwater collection has been practiced for centuries as ancient civilizations. In Hellas (Greece), they used to do this as early as the Minoan period (3200-1100 BC) due to a lack of water (Antoniou et al., 2014). On the basis of archeological evidence, the Minoans (c. 3200–1100 BC) possessed a very advanced understanding of water management by adopting very advanced hydraulic systems, for instance, wells, cisterns, and highly developed drainage networks (Angelakis et al., 2013; Angelakis & Koutsoyiannis, 2003). To mitigate seasonal water shortages, for example, researchers have identified advanced conduits and sedimentation basins within the Palace of Knossos that are designed to collect and store rainwater (Koutsoyiannis et al., 2008). In addition to providing domestic water requirements, these ancient technologies also served to prevent flood damage during high precipitation periods. The fundamental principles of Minoan cistern design have a lot to offer to modern rainwater harvesting practices. These included effective capture of runoff, natural filtration using local resources, and balancing with nature. To deal with the current water shortage issues as well as increase ecosystem resilience, engineers tend to integrate such time-tested design techniques in conjunction with the application of contemporary technologies. Various collection systems and cisterns of storage evolved over time, with significant advancements in the Hellenistic period (323 – 30 BC)(Yannopoulos et al., 2017).

Rainwater harvesting has been a vital adaptation strategy to climate change, particularly against extreme events like drought and aridity (Pandey et al., 2003). All evidence shows a relationship between variability of climate and increased efforts to construct rainwater harvesting structures in different regions of the globe (Pandey et al., 2003). They have been used in areas of uneven water distribution and dry or semi-dry climatic regimes, providing flood protection and making water available during drought (Baba et al., 2018). The chronology of the development of rainwater harvesting technologies provides evidence for the importance of water conservation throughout history (Yannopoulos et al., 2017).

The recent developments in rainwater collection and storage have also led to their growing popularity and usage worldwide (Gould, 1992; Heggen, 2000). Advances in technology in the areas of roofing, guttering, storage, and protection against water quality have improved rainwater harvesting systems (Heggen, 2000). The systems are currently applied in developing countries as well as economically developed nations, with applications ranging from traditional homes to modern urban designs (Heggen, 2000; Sojka et al., 2016). Pursuing these advances, contemporary urban building design more often integrates rainwater harvesting aspects into shape and building codes (Sojka et al., 2016; Heggen, 2000). For instance, permeable pavement, green roofs, and bio-retention cells are now common elements in newly built residential developments, signifying a greater trend towards ecologically sound building design. These methods, combined with cutting-edge engineering plus heritage-inspired water management practices, not only counteract water shortages but also align with broader sustainability objectives, such as stormwater runoff reduction, enhancing urban microclimates, and livability improvement in the urban setting (Sharma et al., 2016). This intersection serves to emphasize the benefits of combining proved techniques with new technologies in order to develop resilient, climate-resistant urban environments. Rainwater harvesting (RWH) offers multi-faceted benefits far beyond simple water preservation.

By effective collection and storage of rain, RWH systems also aid in stormwater management as well as groundwater replenishment with minimal dependence on centralized utility water systems (Sojka et al., 2016). In modern urban environments, such systems are an important component of integrated water resource management systems that enable cities to mitigate the impacts of heavy rain and prevent surface runoff, thereby decreasing flood hazards and relieving pressure on conventional water resources (Sharma et al., 2016). Despite the advantages, there are daunting challenges in optimizing the effectiveness of RWH systems.

Initial studies (Ietc, 2003; Ashok K. Sharma et al., 2016) indicate that although decentralized systems can potentially enhance freshwater availability and minimize reliance on large-scale infrastructure, they are oftentimes hindered by uneven rainfall patterns, high initial investment, and maintenance requirements. Besides, there is morphological and local climate heterogeneity that occurs in cities, making sophisticated packages of simulation necessary—such as SWMM integrated with GIS—so that runoff may be simulated efficiently and optimal system design is obtained (Sharma et al., 2016). To address these concerns, holistic approaches to water resource management must be adopted that incorporate effective data collection, real-time monitoring, and forecasting modeling.

Such combined measures enable city planners to plan RWH systems that respond to local circumstances, whereby water catchment, storage, and distribution processes are appropriately assessed and optimized. Local authorities also can facilitate the implementation of RWH by instituting policy measures—like economic incentives (e.g., tax credits, subsidies, and low-interest loans), revised building codes, and public education campaigns—that emphasize both the financial and environmental benefits of such systems. Moreover, RWH, when complemented by complementary strategies—such as water recycling, permeable pavement, and green roofs—is observed to significantly enhance overall advantages.

Not only does such complementarity reduce municipal water consumption and improve water quality, but also urban resilience is promoted through groundwater level retention and reducing the impacts of climate variability risks. Ultimately, through the integration of traditional water harvesting approaches and advanced technological innovations, urban cities can form resilient and viable models of water management that integrate greater Sustainable Development Goals while fostering long-term environmental and economic sustainability. Rainwater harvesting is now an element of integrated urban water management practice in modern cities, driven by the practice of ecological sustainable development and urbanization (Ashok K. Sharma et al., 2016). It has worked both in rural and urban settings, particularly in developing countries like India (Nicholas L. Cain, 2014).

Rainwater collection together with water recycling can mitigate water scarcity in cities where water is often wasted (V. Pavan, 2012). However, there are still difficulties in understanding its full potential in today's cities, for example, impacts on water demand, public health, energy use, environmental effects, and cost-benefit (Ashok K. Sharma et al., 2016).

2.2. Ancient Water Storage Techniques

One of the most urgent and obvious effects of climate change is aridification, and water management has become an ever-increasing priority issue all over the world. According to archeological data, ancient civilizations used a variety of surface water management practices to cope with aridity, from flood defense buildings to sophisticated rainwater harvesting systems (Charlesworth et al., 2016). The development of such approaches places prominence on the interactions between water resource sustainability and climate adaptation, a challenge that continues to this day (Charlesworth et al., 2016). Civilizations throughout history have developed intricate water control systems to fulfill urban as well as agricultural needs, particularly in desert and semi-desert environments. The achievements of ancient civilizations to provide appropriate management of water are rich with lessons for contemporary sustainable water management approaches. Historically, archaeologists have shown a special interest in the role of water management in ancient societies, uncovering information regarding advanced hydraulic engineering, mechanisms of governance, and adaptive principles that allowed societies to endure harsh climatic conditions (Kaptijn, 2017). Such studies highlight the complicated interdependence between human settlement patterns, technological advancement, and climatic adaptation. Through the analysis of past water systems, we can identify practices that have worked in the long term and assess their applicability to contemporary situations (Fig. 5) (Kaptijn, 2017).

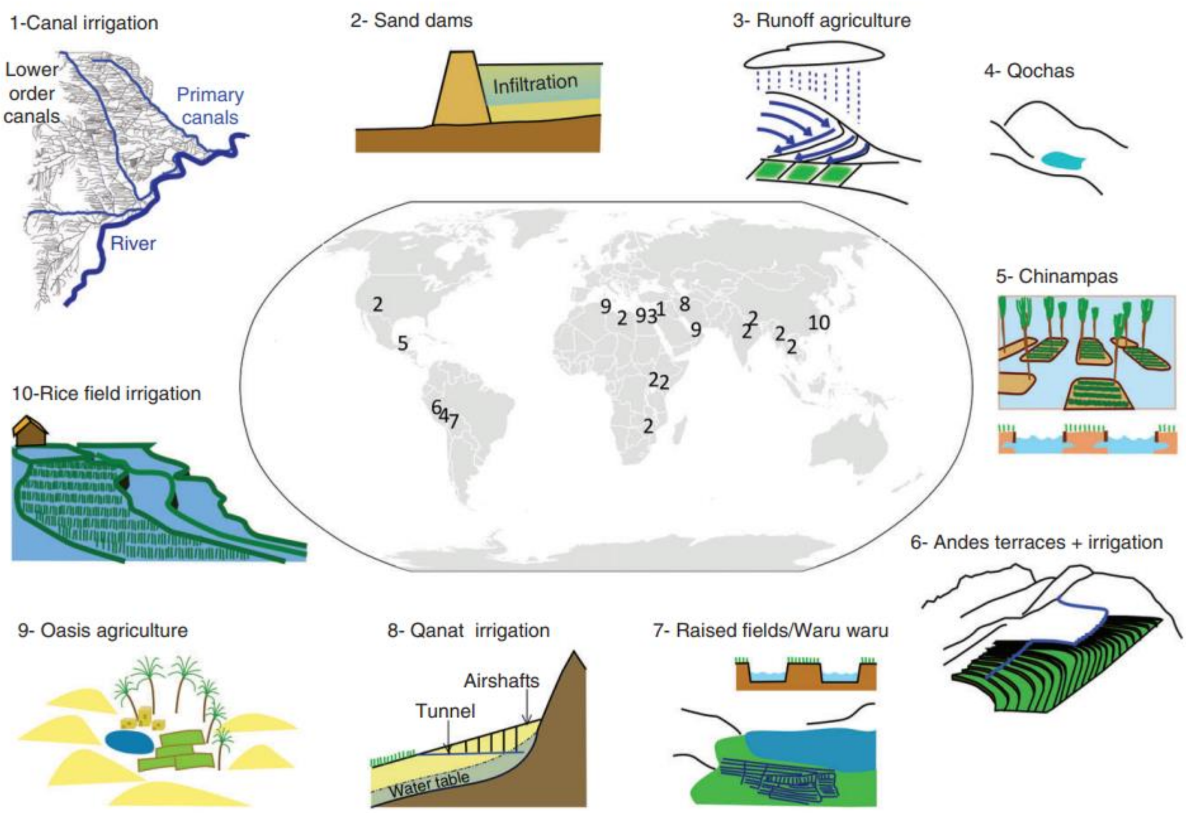

Fig 5. The location of the water management techniques and their schematic layout (Source: Kaptijn, 2017)

Ancient civilizations demonstrated remarkable resourcefulness in designing water storage and management systems to meet both city and farm demands. These systems possessed immense diversity in complexity and design, based on regional climatic circumstances, local materials, and socio-political structures. Aqueducts, cisterns, reservoirs, stepwells, qanats, and rainwater harvesting pools were used by different civilizations (Feo et al., 2010; Barghouth

& Al-Sa'ed, 2009). The qanat system, a most dramatic example, has played a key role in Iran's water supply for over two millennia (Fig. 6). This underground system of tunnels, which sends water from highland aquifers down to the lower ground under the force of gravity, significantly eliminates evaporation and supplies a sustainable water source to arid and semi-arid areas (Manuel et al., 2017). Iran has the world's highest number of qanats, several of which exceed 70 km in length, such as the ancient qanat of Gonabad (Manuel et al., 2017). Sustaining a steady and consistent supply of water, these networks not only encouraged agricultural growth but also shaped urbanization and patterns of settlement.

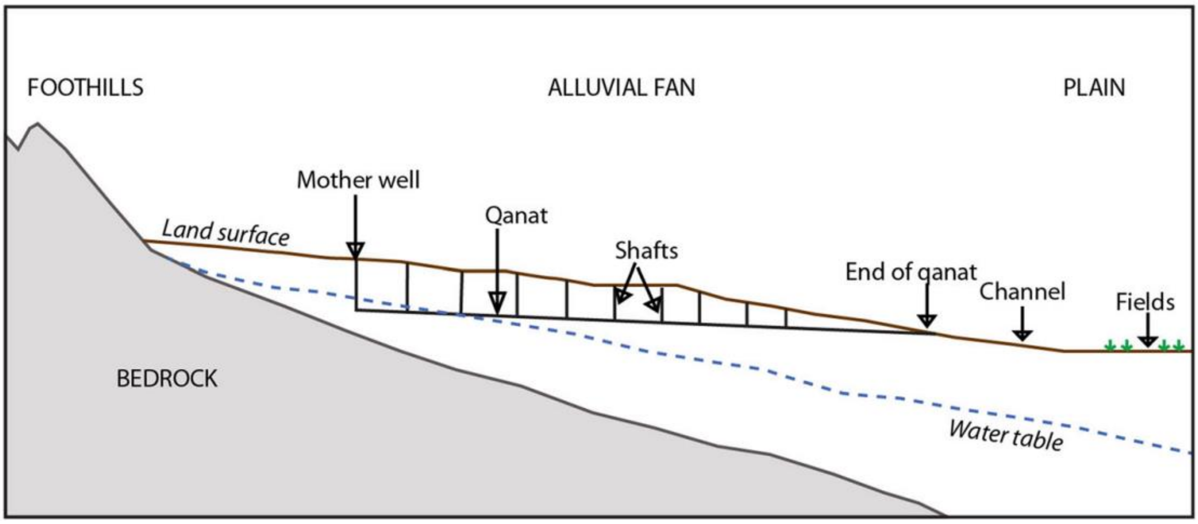

Fig 6. Diagram showing the movement of water from upland to lowland regions by a qanat (source: Manuel et al., 2017)

Urban rainwater harvesting was considered as part of the systematic water system of a city. A complete model of the urban water system of Chinese cities was first developed at the Han Chan'an city, the capital city of Han Dynasty, at around 200 BC. This model influenced urban water system design and construction in the subsequent dynasties of China until the early 19th century. As indicated by Fig.7, this model consisted of different components, including urban rivers, ponds, moats and drainage rivers (Yun Zheng, 2015).

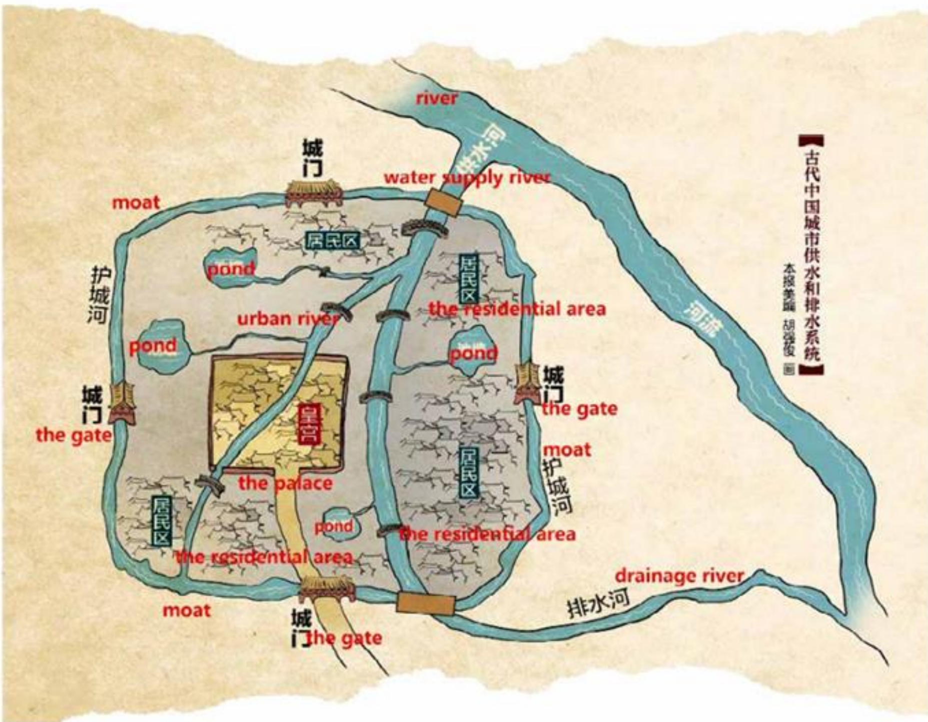

Figure 7. General form of an ancient urban water system in China.

The majority of these traditional systems formed the basis of modern sustainable water management strategies, with much to inform us regarding resilience, efficiency, and sustainability. Riverbanks—particularly riverbanks of major rivers like the Yellow River—were among the most favored locations to settle in ancient times (Huai Chu, 2005). Proximity to a river was convenient as far as getting water was concerned but also placed the inhabitants at tremendous risk, like vulnerability to heavy rain. Therefore, one of the essential roles of urban water systems was to deal with rainstorm water effectively.

Similar to the gigantic reservoirs or barays of Angkor Wat, ancient water storages played a crucial role in maintaining water supply during dry seasons and controlling floods during rainstorms (Coe, 2003). These barays, with a capacity of up to 48 million m^3, demonstrate the ingenuity of ancient civilizations in controlling water at such large scales. This integration of storage, distribution, and flood management systems assured long-term sustainability, a concept that is highly relevant to contemporary water resource planning. Similarly, the ancient Ventotene reused cisterns reflect a similar mindset, with harvested rainwater being stored and conserved carefully to support human habitation in an environment with limited freshwater resources. Their upkeep and design strategic thinking attest to the success of ancient engineering in developing sustainable water supply measures (Charlesworth et al., 2016).

Fig 8. West baray, Angkor Wat, Cambodia, still containing water. (Wikimedia by Dario Severi: https://commons.wikimedia.org/wiki/File:WestBaray.jpg).

The ancient Greek and Roman civilizations also made significant contributions to water infrastructure by addressing urban drainage within stormwater management strategies. Terracotta sewers and sewer tunnels were typical elements of the systems that diverted rainwater into holding basins for subsequent use, reducing the risk of flooding and water shortages (Charlesworth et al., 2016). Other historical records indicate that rainwater harvesting was part of the mainstream in ancient Mediterranean societies, and Minoan civilization in Crete built enormous systems of cisterns for domestic and agricultural use (Charlesworth et al., 2016).Similar to Angkor Wat's giant reservoirs or barays (Fig. 8), ancient water storage structures played a vital role in making available water during dry months and controlling floodwaters when storms came (Coe, 2003). These barays, with as much as 48 million m^3 storage capacity, bear witness to the advanced water management capabilities of previous civilizations. The availability of storage, distribution, and flood control systems ensured long-term sustainability, a theme that is no longer of great concern in water resource planning today. Similarly, Ventotene's historic reused cisterns exhibit the same strategy, where rainwater was harvested and stored and monitored with care to maintain human populations in a region of limited freshwater supply. Regular maintenance and deliberate design of such vintage water infrastructure verify the achievement of ancient engineering in creating sustainable water supply alternatives (Charlesworth et al., 2016).

Fig 9. Cistern complex near Chersonisos, Crete. (source: Charlesworth et al., 2016)

These water systems used methods of filtration such as sand and gravel to improve water quality and reduce threats of contamination (Fig. 9) (Charlesworth et al., 2016).There have been allusions of water technology linkages between the Minoan civilization and the Etruscans (Angelakis et al., 2013). The progress of water science was disrupted and hindered during Europe's Dark Ages. However, the Minoans probably established contacts with neighboring cultures, such as the Egyptians, Mycenaeans, Etruscans, and Classical Greeks (Angelakis et al., 2013). In Perugia, in Umbria, a number of water cisterns have been discovered. A main cistern on Via Cesare Caporali was discovered by accident in 1989 during building renovations. The Perugia cistern is comparable to those of Minoan Knossos and Archanes. Todi, a town in Umbria, has some 5 kilometers of subsurface tunnel and galleries and over 30 cisterns from the era of the Etruscan civilization.

Fig 10. Terracotta pipe for rainwater harvesting from roofs at Pompeii, Italy. The pipes would have directed water into cisterns to service individual buildings(source: Charlesworth et al., 2016) .

During the Classical and Hellenistic ages, significant advancements in hydraulics revolutionized the understanding and application of air and water pressure. The innovations contributed to the creation of sophisticated hydraulic and pneumatic machines such as water-lifting devices, hydraulic clocks, music instruments, steam boilers, and reacting motors, reflecting an in-depth comprehension of fluid dynamics (Antoniou et al., 2014). For the first time in human history, pressure flow was applied on an extensive technological scale to water transport during these periods. For the first time in human history, pressure flow was applied on an extensive technological scale to water transport during these periods, transforming urban infrastructure and agriculture through systems like elaborate aqueducts and irrigation networks that harnessed the power of fluid mechanics for societal benefit like fig.10 (Lorenz et al. 2022)

Rainwater collection also reached substantial advancements, attested to by the water supply system of the citadel of Pergamon, located in western Anatolia (modern Turkey). The settlement was initially relying on a system of cisterns for rainwater collection to offer war-time water reserves and on a small spring at the foot of the hill. As of 1993 AD, 149 cisterns had been discovered, sufficient to accommodate around 7,900 inhabitants (Garbrecht and Garbrecht, 2005). The Hellenistic period also experienced enormous improvements in water supply systems as well as sanitary procedures in every region of Hellenistic Hellas. Advances in hydraulic engineering at the time also enhanced cistern technologies initially developed by Minoans and Mycenaeans. Some of the advancements included the construction of cisterns with rectangular cross-section and circular cross-section similar to those at Lato, Dreros, Santorini, Amorgos, and Delos. Cisterns in fortresses were either partially or completely carved from rock, for instance, at the island of Rho (Antoniou, 2012). A few ancient rainwater cisterns remain from these homes, including pear-shaped structures in Santorini, Delos, Aegina, Amorgos, and Polyrrhenia. To prevent water leakages, the cisterns had at least one layer of hydraulic plaster applied and usually a capacity of approximately 10 cubic meters.

In addition to these lesser cisterns(Fig.11), much larger ones were constructed in rock fortresses. These buildings have excellently designed and geometrically precise plans, such as the giant rainwater cistern at the Theatre of Delos, Greek (Fraisse and Moretti, 2007).

Figure 11. Hellenistic cisterns: the main cistern (possibly originally covered) at Elanion sanctuary in the island of Aegina (left) and the slab-covered cistern of the sanctuary of Heraion at Loutraki Attika (right)

2.2.1. Urban Water Storage Tanks and Their Legacy

Water storage tanks have been a vital component of urban water management dating back to ancient times. Rock-cut cisterns and reservoirs were constructed by ancient Mediterranean civilizations to collect and store freshwater and rainwater to create a steady supply for consumption, irrigation, and industry (Mays et al., 2013). The elaborate system of underground water tanks in Alexandria, Egypt, demonstrates the level of sophistication employed in these methods, where tanks of several tiers collected water from the Nile River in addition to rain (Spanoudi et al., 2021).
Similarly, water tanks that are fortified and Indian temple reservoirs, such as the Rajasthan stepwells and the Tala tank in Kolkata (which was built in 1911), bear witness to the timelessness of well-conceived buildings (Pal Amitava et al., 2019). The systems remain operational even today, providing essential water storage in addition to being heritage buildings that testify to centuries of hydro-engineering advancements (Sangiorgio et al., 2020). Their legacy remains evident today, with numerous examples found worldwide.

2.2.2. Rainwater Harvesting and Multi-Use Water Storage

In addition to large-scale reservoirs, many ancient civilizations employed rainwater harvesting techniques to supplement water supplies. The Greeks, for instance, used rooftop collection systems and underground storage tanks as early as the Minoan period (3200–1100 BC) (Yannopoulos et al., 2017). In the arid regions of the Middle East and North Africa, domed rainwater collection structures were constructed to maximize water capture while minimizing evaporation (Ferrand & Cecunjanin, 2014).
Rock-cut fish tankck to the Roman and Byzantine eras, were found along the coasts of Crete and other Mediterranean regions (Davaras, 1974; Oikonomou et al., 2023). These structures, often cut directly into rock and lined with plaster, served a dual function: storing water for human use and maintaining fish stocks as a supplementary food source. In Britain, unique circular lead tanks were developed, possibly serving multiple functions, including water purification and religious ceremonies (Guy, 1981). These tanks not only provide insight into

ancient water storage but also offer valuable data for paleoenvironmental reconstructions and climate change studies (Oikonomou et al., 2023).

2.3. Repurposing Ancient Water Systems for Modern Use

The sustainability principles embodied in these ancient systems highlight key lessons for contemporary water resource management. The durability and efficiency of traditional structures underscore the importance of low-energy, decentralized water storage solutions that can function without reliance on modern electricity-driven infrastructure. Many of these historical techniques, such as qanats, stepwells, and rainwater harvesting tanks, are now being reconsidered for their potential role in climate-resilient water management strategies (Zhou et al., 2022; Bhattacharya, 2015). Ancient tanks in South Asia have been identified as valuable water storage systems that can be restored and adapted to address climate change impacts and water scarcity. Studies have shown that rehabilitating these tanks can improve irrigation, groundwater recharge, and crop productivity while providing social and environmental benefits (Perera et al., 2020; Gujja et al., 2009).In India, restoring temple tanks in urban areas has been proposed to reestablish their hydrological role and enable multiple uses (Ganesan, 2008). Improved management techniques, such as implementing water control systems and closing sluices on rainy days, can increase irrigation efficiency and reduce crop failure risks (Oppen, 1987). Additionally, adapting traditional water management methods has proven to be a cost-effective and socially acceptable approach compared to large-scale water infrastructure projects (Gujja et al., 2009).

The people of ancient India developed methods to effectively utilize water resources to fulfil their diverse requirements while also ensuring that rainwater harvesting contributed to the replenishment of these resources (Fig.12). Their extensive history of traditional water management and harvesting techniques remains a source of valuable insights even in modern times (Fig.13). In India, restoring temple tanks in urban areas has been proposed to reestablish their hydrological role and enable multiple uses (Ganesan, 2008). Improved management techniques, such as implementing water control systems and closing sluices on rainy days, can increase irrigation efficiency and reduce crop failure risks (Oppen, 1987). Additionally, adapting traditional water management methods has proven to be a cost-effective and socially acceptable approach compared to large-scale water infrastructure projects (Gujja et al., 2009). In India, traditional water systems emphasized conservation principles. Indigenous methods utilized water from sources such as mountain streams, springs, shallow aquifers, and rainwater collected in tanks and ponds to meet drinking and domestic needs. Depending on water quality, specific traditional sources were allocated for activities like drinking, bathing, or washing.

Figure 12. Traditional water harvesting systems continue to provide water in various regions across the country, such as the Adalaj Ka Vav stepwell in Gujarat. Photo credit: Ganesh Pangare.

Figure 13. Traditional Water Lifting Device, Orissa. Photograph: Ganesh Pangare.

These studies indicate the potential for reviving aged tank systems as a green climate change adaptation measure for water management. These old reservoirs, typically located with care in areas of scattered rainfall or variable seasonal water availability, were constructed to catch and store runoff for home consumption, agricultural use, and ecosystem requirements (Perera et al., 2020; Zhou et al., 2022). Through forming a natural buffer against flood and drought, reinstated tank systems stabilize local water levels and reduce stress on modern infrastructure. They also offer low-energy, low-cost solutions in contrast to high-cost, high-energy schemes like dams and desalination plants that carry large capital costs and can be massive ecological risks (Gujja et al., 2009).

Other than water security, rehabilitated tank systems have the potential to yield a variety of co-benefits. When integrated with green infrastructure such as constructed wetlands, riparian buffers, and permeable pavements, tanks can facilitate groundwater recharging, maintain ecological conditions, and improve local agriculture (Sivaraman et al., 2022; Bhattacharya, 2015). They are also critical for community management of water, which ensures local participation in maintenance and decision-making. Such engagement enhances social cohesion, preserves cultural identity, and is in harmony with climate adaptation efforts recommended by international initiatives like the Sustainable Development Goals (SDGs) (Zhou et al., 2022). In practice, historic tank revival is an applied harmony between ancient prudence and modern scientific practices, upgrading resilience against climate variability. Adaptive reuse of historic infrastructure has numerous benefits but poses dire challenges.

Conversely, the reuse and recycling of centuries-old structures—e.g., heritage sites, stepwells, and ancient tanks—is a component of sustainable development, as it minimizes the exploitation of resources and prolongs the life of the materials in place (Popescu & Staicu, 2022). Restoration also preserves cultural heritage, rejuvenates neighborhoods, and can also serve as an economic and tourism driver (Maha Shree J et al., 2024). By being aligned with circular economy strategies, adaptive reuse reduces construction waste at sites and carbon emissions from new construction (Popescu & Staicu, 2022). Despite this, the challenges in adaptive reuse are multifaceted.

Authenticity is ensured with utmost care for historical truth, architectural authenticity, and intangible cultural heritage (Viola & Diano, 2019). Planners and engineers must optimize resources so the renewed infrastructure meets the safety requirements of today, the energy efficiency norms, and users' expectations (Hein & Houck, 2008). The repair process may involve detailed feasibility studies, structural repairs, seismic retrofitting, and the integration of new technologies such as sensor-based monitoring (Viola & Diano, 2019). The involvement of local stakeholders' community participation is also critical, as they provide beneficial site knowledge regarding history, maintenance culture, and cultural significance (Sivaraman et al., 2022). When well implemented, adaptive reuse projects yield long-term social and environmental gains—less sprawl, sense of place, and proof of sustainable resource utilization (Popescu & Staicu, 2022).

Ethics must also be kept in mind, so that cultural heritage is not lost but maintained and any changes remain faithful to the spirit of the original work (Maha Shree J et al., 2024). Future collaboration between historians, conservators, engineers, and the local communities will be essential in the successful overcoming of these challenges, thereby enabling heritage buildings to be living, dynamic resources within the modern urban landscape.

2.4. Sustainable Water Management Practices

Sustainable water management integrates environmental, social, and economic objectives to address issues like urbanization, population growth, and climate change (Mulyana & Moersidik, 2018). Based on the Brundtland Report definition of sustainable development—\"meeting present needs without compromising future generations,\" Sustainable Water Management (SWM) emphasizes equity in space and time as well as protecting ecological integrity (United Nations, 1987; Russo et al., 2014).

In its core, SWM is driven by the key principles of sustainability and sustainable development through highlighting continuous improvement in performance measurement. Enhanced feedback through properly selected criteria and indicators is necessary for monitoring the effectiveness of water management actions (Heintz, 2004). For instance, the Sustainable Water Resources Roundtable (SWRR) framework emphasizes geographic and temporal scalability in indicator development in a manner that takes into consideration regional hydrologic variability as well as future climate projections to be anticipated (Smith & Zhang, 2006; Russo et al., 2014). Decision support systems (DSS) play a central role here in terms of sophisticated analytical tools that facilitate advanced decision-making approaches to water resource management. These systems integrate hydrological modeling, Geographic Information Systems (GIS), and real-time information to enable management scenarios assessment, thus optimizing resource utilization and identifying potential areas of weakness or vulnerability (Simonovic, 1996). The SWRR has provided a conceptual framework and guidelines for selecting indicators of sustainability, in recognition of the utility of systems analysis in understanding and measuring sustainability (Smith & Zhang, 2006).

Major principles of SWM are taking into account long-term effects, paying attention to significant geographic and temporal scales, and making indicators measurable and scientifically grounded (Smith & Zhang, 2006).

These indicators are not only able to seize the present state of water resources, but also to forecast the effects of climate variability and anthropogenic forcing on future water availability. Furthermore, recent bibliometric studies have established the heightened global research focus on sustainable water resource management, driven by such issues as climate change and increasing water scarcity (Durán-Sánchez, Álvarez-García, & del Río-Rama, 2018). This mounting literature buttresses the need for flexible as well as evidence-based integrated water resource management practices. By combining advanced technologies, sound policy frameworks, and sound performance indicators, SWM strategies can be built to ensure equitable distribution of water resources in the present and preserve the ecological and social foundations required for a sustainable future (Heintz, 2004; Smith & Zhang, 2006). Overall, SWM systems require a concerted, multidisciplinary approach that utilizes technical innovation as well as strong institutional support. Such collaborative model not only addresses present-day water demand but also increases resilience against future environmental threats—a goal that is pivotal for long-term water security and sustainable development.

Rainwater harvesting (RWH) is recently attracting attention as a water-saving water management choice, particularly in water-scarce regions (Rahman, 2017). Deployment of RWH technologies into development projects can significantly improve household livelihoods, with cost being a major limitation (Wekesa et al., 2023). RWH technologies have once again gained attention as a sustainable water management practice, particularly in water-scarce regions. Deployment of RWH in development projects can significantly improve household livelihoods; however, cost is a major limitation to large-scale deployment (Wekesa et al., 2023). A survey of funding sources for adoption of RWH (Fig. 14) discovered that 88% of the interviewed respondents used the household head as the main source of income for buying or installing RWH systems. On the other hand, 6% said that money came from the community, 5% said money came from self-help groups, and 2% said money came from the county government. These findings highlight the economic burden on single families, and how little role outside sources of finance play in subsidizing RWH uptake. Addressing these economic issues may be the key to enhancing RWH adoption in vulnerable communities. (Wekesa et al., 2023)

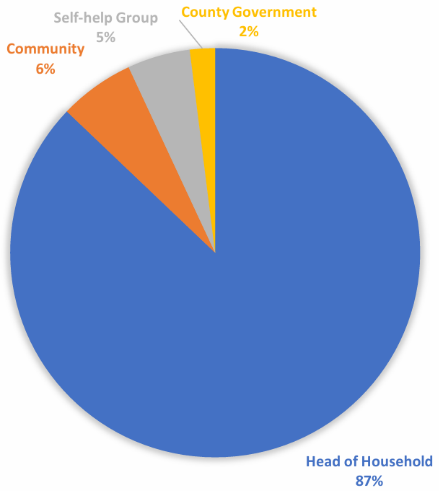

Figure 14. Source of capital to purchase rainwater harvesting technologies (Source: Wekesa et al., 2023)

To determine optimal RWH application, researchers have applied Geographic Information Systems, remote sensing, and multi-criteria analysis, which align with Sustainable Development Goals (SDGs) (Ezzeldin et al., 2022). A new approach combines RWH with integrated farming systems to address clean water need and support agriculture and aquaculture (Wibowo et al., 2022). Effective RWH application entails considering a variety of factors such as water quantity, quality, economic viability, and local policies (Rahman, 2017). Government support in the form of subsidy, training, and partnership with development agencies can facilitate extensive application of RWH technologies (Wekesa et al., 2023).In the United States of America, Texas and Hawaii states have created policies that promote RWH, including tax exemptions and financial aid for rainwater harvesting projects (NTO Tank, 2024; World Water Reserve, 2024). The U.S. Environmental Protection Agency (EPA) has also established guidelines to help municipalities put RWH policies in place, highlighting its application for sustainable urban water management (EPA, 2024). As water scarcity is exacerbated by climate change, the inclusion of RWH as part of a more comprehensive water management approach is a viable option. These studies indicate the suitability of RWH for supporting sustainable development and the attainment of water-related SDGs.

In this perspective, both decentralized and centralized water management systems have inherent strengths and weaknesses. Decentralized systems are more cost-effective and offer better service coverage compared to centralized systems (Pearce-Oroz, 2006). Decentralized systems also show better practice due to increased political accountability and sustainable management incentives (Pearce-Oroz, 2006). Decentralized systems face the challenges of tariff design and depreciation management (Pearce-Oroz, 2006). Decentralized control systems have lower operation and maintenance expenses but higher initial hardware and software expenses in desalination plants (Seoudy et al., 2024). Centralized systems can provide higher aggregate net benefits but can be less incentivized to use by individuals (Yi Xiao et al., 2018). Integration of decentralized systems with centralized systems involves complex interactions that impact water availability, quality, energy use, and other socio-economic factors (Arora et al., 2015). A proper evaluation of alternative water supplies needs an economic, social, and environmental framework (Arora et al., 2015).

2.5. Impact of Climate Change on Water Resources

Anthropogenic climate change is exerting very profound impacts on the hydrological cycles of our planet, with ensuing extreme variations in global precipitation and evaporation patterns. (Konapala et al., 2020). These in turn directly impact regional water resources' availability, with serious implications for human society and ecosystems. Climate change is revealed by research to affect not just annual mean precipitation and evaporation, but also to alter their seasonal patterns significantly. Such seasonal variations may have the potential to increase the intensity of extreme events such as floods and droughts, particularly in regions already typified by extremely variable precipitation. Non-parametric analysis of the climate records also shows complex patterns of seasonal changes in precipitation and evaporation across the globe that warrant closer scrutiny and detailed examination. Lastly, this kind of information regarding the changes and their impact on available water is most important to future safe and effective water resource planning and management, and to minimizing the exposure of societies and ecosystems to the impacts of climate change (Konapala et al., 2020). Konapala et al. (2020) have listed nine hydroclimatic regimes in the world among which four have higher variability of precipitation and five have lower evaporation variability with higher mean precipitation and evaporation.

These are creating more erratic seasonal patterns in already erratic regions. Temperature is increasing and the precipitation regimes are changing in the USA and Africa, affecting water resources that range from long-lasting droughts to increased aridity (Etukudoh et al., 2024). Besides, intensification of the extreme climate events, as more and intense storms, has caused short-term flooding and long-term alterations in the availability of water. Evidence indicates that regions whose traditional water cycles were previously predictable now experience greater uncertainty, complicating water management and agricultural planning. More specifically, extended droughts are accelerating desertification in parts of Africa and increased precipitation variability is putting a strain on infrastructure in North America. This calls for immediate need for adaptation measures, i.e., better watershed management, funding for water-saving technology, and policy interventions involving climate resilience as part of water management. (Etukudoh et al., 2024). Pakistan, for instance, has been plagued with water scarcity challenges as a result of the impacts of climate change on the frequency and intensity of rain, which affect agricultural yields and food security (Waqas et al., 2021). This complex interaction of factors calls for adaptation strategies, i.e., water saving, infrastructure, and sustainable approaches to respond to the climate change challenges and provide water supply. Also Europe is increasingly facing water-related challenges due to climate change, including more frequent droughts, shifting precipitation patterns, and heightened pressure on freshwater resources."

Climate change poses significant challenges to water resource management and requires adaptive strategies. Studies indicate that climate change is causing decreasing rainfall, increased droughts, and decreased groundwater levels (Mahdhi et al., 2019). Adaptation strategies in irrigation include good maintenance, water conservation methods, and modification of crop systems (Mahdhi et al., 2019). In reservoir systems, updating curves via optimization algorithms is more favorable, while low impact development methods are more favored for flood control (Elgendy et al., 2024). The adoption of adaptation practices in agriculture, such as cropping pattern shifts, effectively restricts climate change caused adverse effects on water resources (Ashofteh et al., 2019). Integrated water management approaches in sustainable development and Millennium Development Goal achievement rely upon climate variability impacts (Kashyap, 2004). Development of adaptive capacity in water management, e.g., access to early warning and impact analysis, is essential to reduce vulnerability and facilitate sustainable livelihoods (Kashyap, 2004).

Recent research also highlights the fact that as natural sources of water face stress through climate extremes, RWH re-emerged as a potential climate adaptation measure (Nandi & Gonela, 2022). According to their systematic review, Nandi and Gonela (2022) observe that rain extremes caused by climate change can be mitigated somewhat by harvesting and storing rain for later domestic use. This can enhance resilience in rural and urban settings via diversification of sources of supply of water. But they also note that effective RWH implementation under climatic unpredictability relies on facilitating utility policies, stakeholder participation, and continuous monitoring of precipitation trends in a bid to maximize tank capacity and sizes of distribution networks. Consequently, climate change not only amplifies water scarcity but also triggers innovation in water management in terms of holistic RWH techniques and advanced decision support systems to ensure long-term sustainability.

Overall, the interaction of changing precipitation regimes, hydrological regimes, and social governance demands a multi-dimensional climate adaptation strategy. While immediate solutions of crop modifications and infrastructure improvements continue to be crucial, tapping rainwater harvesting can also play an additional water security role. As Nandi and Gonela (2022) point out, balancing engineering, policy, and community perspectives will become necessary to addressing the added challenges that climate change presents in global water resources.

Ancient water management systems have demonstrated remarkable resilience and sensitivity to climate change and have offered valuable lessons for modern water management practice. Traditional approaches like Spain's acequias de careo (Civantos et al., 2023) and China's Grand Canal's distributive hydraulic engineering approach (Xu et al., 2022) have functioned effectively in managing water resources in an environmentally friendly way for centuries by effectively redistributing and managing water for irrigation, flood control, and trade .These examples point out that decentralized, low-energy, climate-resilient water infrastructure was created by pre-industrial societies as they were properly planned in accordance with the local hydrology and climatic conditions. Similarly, qanats in Persia, stepwells in India, and Bali’s subak system showcase sustainable techniques that optimize water storage and minimize losses through gravity-fed distribution and community-driven governance (Goblot, 1979; Livingston & Beach, 2002; Lansing, 2006). These traditional approaches emphasize nature-based solutions and adaptive infrastructure, offering valuable insights for modern water policies that integrate GIS modeling, remote sensing, and climate forecasting to enhance water resilience and sustainability.

In addition to coupling natural processes with engineered solutions, traditional water management systems evolved as integrated systems that included vegetation management, soil conservation, and surface and groundwater management. This holistic approach not only optimized the utilization of water but also ensured far-reaching environmental, social, and economic co-benefits through ecosystem protection and enhanced local resilience (Civantos et al., 2023). These systems enabled the communities to maximize water availability for both domestic and agricultural use and, meanwhile, preclude soil erosion and groundwater level maintenance.

These age-old techniques continue to offer valuable lessons for contemporary city planning. Contemporary cities, with their increased climate unpredictability, can retranslate these principles into building resilient water systems that take in and direct rainfall more successfully, reducing the risks of floods, water scarcity, and land erosion (Bhiwandiwalla, 2021). Through the adoption of decentralized water harvesting and natural filtration systems, city planners can reduce the dependence on energy-intensive centralized systems and ensure a more sustainable water supply.

Additional perspective on the development of such systems is provided by archeological studies that give comprehensive accounts of long-term planning and adaptive strategies that maintained water management for millennia (Kaptijn, 2018). Such studies highlight the ancient techniques' profound embedding within local cultural and environmental practice and their technical creativity. This synthesis can aid current water management practice by incorporating traditional knowledge with emerging technology like remote sensing, GIS-based modeling, and real-time climate monitoring. Against the backdrop of continuous climate change, this synthesis may result in the creation of integrated and adaptive water management strategies that build urban resilience (Kaptijn, 2018; Xu et al., 2022).

Finally, though they may not offer the solution to every modern water management issue, traditional approaches offer a useful blueprint for creating systems that are both flexible and sustainable. Modern solutions can, by drawing on the past, better balance environmental, social, and economic pressures, ensuring a more sustainable water future for cities.

2.6. Advancements concerning technology

Technological developments have demonstrated that there are numerous approaches to rainwater and stormwater assessment. The important thing is to determine which of them is the best option for the particular issue at hand. In today's urban environment, advancements such as high-resolution remote sensing, Geographic Information Systems (GIS), and hydrological simulation models (e.g., SWMM) offer powerful means to analyze and manage rainwater and stormwater runoff with greater accuracy (Xu et al., 2022; Civantos et al., 2023). These models are further enhanced by real-time data collecting using Internet of Things sensors, which offer dynamic feedback necessary for timely decision-making in flood control and water resource management (Nandi et al., 2020). Furthermore, new hybrid systems that integrate machine learning methods with conventional hydrological models aid in reducing uncertainty in rainfall forecasting and extreme weather events (Etukudoh et al., 2024). The particular difficulties of a particular urban environment, including as geographical variability, infrastructural limitations, and the requirement for adaptive management in a changing climate, ultimately determine which stormwater assessment approach is best.

The Sustainable Urban Drainage Systems Manual (Bridget Woods Ballardet al.,2015) provides a technical description of some of the several Sustainable Urban Drainage Systems kinds, which are mentioned below:

- Rainwater harvesting
- Green Roofs
- Infiltration systems
- Proprietary treatment systems

- Filter strips
- Filter drains
- Swales
- Bioretention systems
- Trees
- Pervious pavements
- Attenuation storage tanks
- Detention basins
- Ponds and wetlands

2.6.1. Smart technologies and IoT (Internet of Things) applications in water harvesting systems

Recent research looks into IoT solutions for smart water harvesting systems to address issues of water scarcity and maximize resource efficiency. With the use of networked sensors, self-sensing controls, and real-time computing, the systems become more efficient and responsive to provide optimal water utilization even under fluctuating environmental conditions.

IoT-based solutions offer real-time water quantity and quality monitoring through sensors and microcontrollers (Movva, 2023). These offer continuous data on parameters such as pH, turbidity, dissolved oxygen, and flow rates, which allow early detection of contamination and system inefficiencies. For instance, cloud-IoT platforms can also be used to process real-time sensor data and carry out automatic action, for instance, adjusting water flow or activating filtration systems when contaminated (Gupta et al., 2021). For atmospheric water harvesting from humid air, smart atmospheric water harvesting systems use solar power and Internet of Things devices. Self-regulating environment condition monitoring delivers optimal efficiency and energy usage (Sudarshan et al., 2020). Machine learning models for forecasting atmospheric humidity levels have further improved such systems by enabling adaptive water extraction rate adjustments (Patel et al., 2022). IoT sensors can be integrated with blockchain technology to create tamper-proof and transparent water usage records, boosting the efficiency of water harvesting tanks (Maulekhi et al., 2020). This decentralized network facilitates safe storage of data and traceability without unauthorized access or manipulation of water usage records (Li et al., 2023). Smart water systems in urban areas also employ various technologies like microcontrollers, sensors, and communication modules to conserve and regulate water resources effectively (Okoli & Kabaso, 2024). The systems enable predictive analytics for leak detection, forecasting water demand, and adaptive pressure management of urban pipes (Kumar et al., 2023). Integration of 3D printing and solar energy with IoT-based smart water networks can potentially maximize sustainability (Okoli & Kabaso, 2024). The use of 3D-printed components reduces material loss as well as production cost, while solar-charged IoT sensors increase energy efficiency in off-grid or rural areas (Rodriguez et al., 2022). These developments demonstrate the potential of smart technologies to improve water harvesting and water management methods by reducing operational costs, increasing efficiency rates, and enabling data-informed decision-making (Ibrahim et al., 2023).

Water treatment and water quality monitoring are now a necessity to supply drinking water safely. Physio-chemical analysis of water, adsorption, and real-time monitoring systems with IoT platforms are employed for water analysis (Singh et al., 2016). Riverbank filtration is a low-cost pretreatment method that has the potential to reduce the cost of membrane treatment by 10-20% (Dalai & Jha, 2013). Advanced spectroscopic techniques and biosensors have improved detection sensitivities for impurities such as microorganisms, pesticides, and heavy metals to portable, real-time monitoring equipment (Zulkifli et al., 2017).

Whereas conventional laboratory methods ensure high accuracy, they are expensive and time-consuming. Against this background, researchers are investigating optical, electrochemical, electrical, biological, and surface-sensing technologies to develop simple-to-use on-site monitoring platforms (Thakur & Devi, 2022). The integration of these technologies with IoT solutions aligns with Industry 4.0 applications in environmental contexts, where automation, artificial intelligence, and sensor-based analytics are at the core of water management that is sustainable (Hossain et al., 2023).

2.6.2. Rainwater harvesting model simulations and optimization tools

RWH systems are increasingly important for sustainable water management and flood mitigation. By controlling storage and distribution, an efficient RWH system may save 58% of water and lower the danger of urban flooding, according to a case study conducted in Malaysia. (Hashim et al., 2013). Simulation-optimization methods have been created in recent studies to design the best RWH systems. For instance, Hashim et al. (2013) created a model that analyzes 20 years of rainfall data to determine ideal tank size (160 m³) and rooftop area (20,000 m²), ensuring adaptability to climate variability. Simulation-optimization approaches integrate hydrological modeling with optimization algorithms to improve water storage, distribution, and reuse strategies. The Malaysia study incorporated water balance equations, first-flush exclusion (0.001 m), and 87% rooftop efficiency into its algorithm, achieving 60% system reliability despite fluctuating rainfall (1,172–2,698 mm annually) (Hashim et al., 2013). Deo et al. (2022) created a model to determine optimal on-farm reservoir sizes for rain-fed farming in India, considering water balance and economic feasibility. Cahyono (2022) developed the RASP model to optimize RWH systems for water supply and runoff reduction in various building types. Schuster-Wallace et al. (2022) introduced an Excel-based Tank Simulation Model to assess RWH potential under current and future climate scenarios. Huang et al. (2015) proposed a simulation-optimization model integrating RWH systems into stormwater management, using fuzzy C-means clustering, BPNN, and tabu search algorithms to optimize spatial design of rain barrels for urban flood mitigation. These studies demonstrate that RWH systems can effectively supplement water supplies, reduce runoff, and mitigate flooding when properly designed and optimized.

2.7. Environmental and Socio-Economic Impacts of Rainwater Harvesting

RWH systems possess several environmental, economic, and social benefits in urban as well as rural settings (Fig. 15). There are particular virtues of such systems in water-short regions of southern Europe, where they can offset 30-40% of the indoor drinking water demand in dwelling buildings and decongest conventional water sources (Santos et al., 2020). Environmentally, RWH can reduce water loss, ensure sustainable water management (Ghanem et al., 2020), and reduce stormwater runoff (Silva et al., 2021). Santos et al. (2020) in Portugal showed that RWH systems can provide 47-50 m³/year non-potable water for flushing toilets and irrigation, significantly reducing municipal water demand. Besides, with climate change regulating precipitation variability and intensity, RWH has further become a key adaptation strategy for climate change. According to Portuguese case studies, RWH systems have stable performance (52-88% efficiency) under both RCP 4.5 and RCP 8.5 climate projections with negligible differences in water savings (€60-€200/year) across different future climate projections (Santos et al., 2020). Studies indicate that the changing rainfall regimes, projected under climate change scenarios (RCP 4.5 and RCP 8.5), can potentially influence the performance of household rainwater harvesting systems so that changes in the storage capacity and system design would be required to maintain optimal performance (C. Santos et al., 2024). For instance, the research revealed that while total yearly amounts of rainfalls can remain the same, more irregular rain distribution requires maximally sized tanks (5-6.5 m³ in the studied houses) in order to ensure stable provision during the dry season (Santos et al., 2020). Economically, RWH can translate into increased profits through enhanced local and farming operations (Ghanem et al., 2020), although cost-effectiveness is subject to local water fees and stormwater charges (Wang & Zimmerman, 2015).

Socially, RWH improves role exchange and responsibility skills (Ghanem et al., 2020). The impacts of RWH technologies on socio-economic conditions do not necessarily have to be significant, with economic ability being a threat to implementation (Bizoza & Umutoni, 2012). Locally, the performance of RWH systems is precipitation-sensitive, system-dependent, and site-specific (Wang & Zimmerman, 2015; Silva et al., 2021). Financial incentives and increased technical expertise are critical for increased adoption and dissemination of RWH systems (Silva et al., 2021).

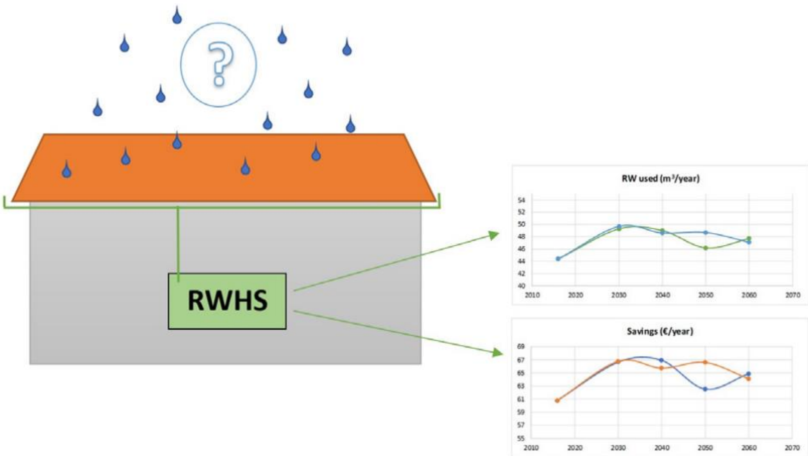

Fig 15. The effect of climate change on domestic Rainwater Harvesting(source: (C. Santos et al., 2024)

2.7.1. Environmental benefits of reducing water runoff and preventing erosion

Soil erosion is a major environmental problem degrading water-holding capacity, soil organic matter, and biodiversity (Zuazo & Pleguezuelo, 2009). Effective erosion control practices are critical in land and water resource sustainable management because if left unabated, this degradation results in decreased agricultural output, increased sedimentation in streams, and long-term ecosystem disruption.

Effective erosion control and land rehabilitation practices are building plant covers and various soil conservation practices (Zuazo & Pleguezuelo, 2008). Experiments in the Shixia Small Watershed indicated that careful land preparation for afforestation, narrow-width terracing, and fish-scale pits are effective in reducing runoff and sediment loss (Cai, 2004). Steep terraces were found to reduce runoff and sediments by 20-45% and 31.5-71.2%, respectively, and nitrogen and phosphorus loss (Cai, 2004). Implementing such conservation practices, cover development, and restoration is vital to protect managed and natural ecosystems (Durán Zuazo & Rodríguez Pleguezuelo, 2008). Water, energy, soil, and biological resources conservation must be prioritized in a bid to have a safe future environment (Zuazo & Pleguezuelo, 2009). With the trend of climate change causing increased instances of extreme weather events, RWH is a natural solution that mitigates the effects of drought and intense rainfall. Simulated future climates suggest that increased variability in the seasonal rainfall pattern could lead to increased numbers of dry spells with more frequent intense storm events, increasing soil erosion threats in unmanaged landscapes (C. Santos et al., 2024, 2024).

In an urban setting, the combination of RWH and green infrastructure practices (e.g., permeable pavement, rain gardens, and bioswales) was discovered to reduce stormwater runoff by 50%, enhancing flood resilience (Shafique et al., 2020) and reducing soir erosion problems.

2.7.2. Social and economic advantages of localized water collection systems

Localized water collection systems, particularly RWH systems offer numerous social and economic advantages. These systems reduce reliance on municipal sources and encourage self-sufficiency in water management by offering a decentralized, affordable substitute for traditional water delivery infrastructure. By guaranteeing a more dependable and accessible water supply during dry seasons and reducing the dangers of supply outages and water restriction, RWH systems can greatly increase family resilience in water-scarce locations (Tavares et al., 2021).

It has been demonstrated that community-wide RWH systems adoption improves regional water security in addition to the benefits to individual households, especially in rural and peri-urban settings where centralized water infrastructure is scarce or unreliable (Ghanem et al., 2020). RWH systems can also help cut infrastructure maintenance costs and postpone the need for expensive capacity expansions in expanding urban areas by lowering demand on overcrowded water utilities (Wang & Zimmerman, 2015). RWH systems promotes sustainable water use practices and environmental care in addition to cost savings. These technologies lessen the contamination of surrounding rivers and groundwater reserves and assist prevent localized flooding by catching rain at its source and minimizing stormwater runoff (Silva et al., 2021). The visible integration of RWH systems can be used as an instructional tool in commercial and institutional contexts, including office buildings and schools, to raise public knowledge and acceptance of alternative water saving techniques (De La Cruz & Gleason, 2018).

While the benefits of RWH systems are well-documented, successful adoption depends on factors such as local climatic conditions, economic incentives, and regulatory support. Policies that provide subsidies, tax rebates, or mandatory installation requirements in new developments can significantly accelerate the adoption of rainwater harvesting technologies and maximize their impact on water sustainability (Maher & Lustig, 2003).

2.7.3. Long-term impacts on water security in island communities like Ventotene

There are critical issues that small island societies face in gaining long-term water security since they are vulnerable to hazards, climate change, and limited resources (Gheuens et al., 2019). Small island societies suffer from water shortage, which is driven by growing demand due to population growth and tourism and reduced supply due to pollution and changing precipitation patterns (Gheuens et al., 2019; Kepel et al., 2023). Climate-related effects such as seawater intrusion, drought, and sea-level rise also threaten water supplies (Kepel et al., 2023). Food insecurity, poverty, and mental illness are linked to water insecurity in the communities (Hanrahan et al., 2016). Awareness improvement, sustainable management practices, and alternative sources of water including rainwater harvesting are some of the solutions to the challenges (Kepel et al., 2023).

According to climate change projections, small island nations will likely experience a 40% reduction in freshwater resources by 2050 if adaptation measures are not taken (The Effect of Climate Change on Domestic Rainwater Harvesting, 2024). As a result, some island populations are setting up Internet of Things-enabled monitoring networks to track water levels in real-time and maximize RWH efficiency (Moglia et al., 2016). Besides, the use of Integrated Water Resource Management (IWRM) approaches in island environments is capable of facilitating adaptive water conserving behaviors and enhancing climatic variability resilience (Paltan et al., 2023).

2.8. Regulatory Frameworks and Policies

2.8.1. Review of international, national, and local regulations on rainwater harvesting

RWH has gained prominence globally as a practice in sustainable water management with diverse regulatory frameworks at the international, national, and local levels. At the international level, the United Nations Sustainable Development Goals (SDGs), particularly Goal 6 (clean water and sanitation), encourage sustainable water management. The implementation is fragmented due to varying regional priorities. For example, countries like Germany, Japan, and Australia have established robust national policies mandating RWH for non-potable uses, supported by technical standards (i.e., water quality standards) and economic incentives in the form of tax rebates or subsidies for tank installation (Pacheco et al., 2017). There are countries that have implemented policies and regulations to promote RWH, particularly in urban areas (Lee et al., 2010; Gouvello et al., 2014).

These policies range from voluntary to mandatory measures, with some nations embedding RWH in broader urban water management plans (Gold et al., 2010; Holland-Stergar, 2018). The success of RWH policies depends on factors like financial investment, laxity of mandate, consumer costs, and support from non-governmental organizations (Holland-Stergar, 2018). Some of the nations that have put in place various RWH strategies, from which nations like France can learn while developing their regulatory frameworks, include Germany, the UK, USA, Brazil, India, Sri Lanka, Australia, and Uganda (Gouvello et al., 2014). The benefits of RWH are many, for instance, supplementing water supplies, managing stormwater, conserving energy, and preventing greenhouse gas emissions (Gold et al., 2010). As water scarcity increases, RWH is likely to become an integral part of future water conservation efforts. The success of RWH policies relies on a number of factors like fiscal investment, flexibility of mandate, consumer affordability, and coordination with non-governmental organizations (NGOs).

For instance, Uganda's NGO-supported community-based RWH schemes have improved rural water access through the combination of local labor with low-cost technologies (Holland-Stergar, 2018). Sri Lanka's top-down approach, on the other hand, encountered resistance due to costly initial investment for households, suggesting the need for phased implementation and generation of public awareness (Gouvello et al., 2014). The benefits of RWH extend beyond water security: it reduces urban stormwater runoff (mitigating flood risks), decreases energy consumption (by reducing the reliance on pumped groundwater), and lowers greenhouse gas emissions (Gold et al., 2010). As water scarcity intensifies, RWH will become a cornerstone of global water conservation strategies, particularly in water-poor settings like the Middle East and Sub-Saharan Africa.

In Italy the Legislative Decree 152/2006, although it does not contain detailed technical specifications for RHW systems, establishes the general principles for the management of water resources, in particular for rainwater. Article 113 regulates the authorisation regime for rainwater runoff and first rainwater, while Article 98 promotes the saving and reuse of rainwater. Some italian regions have legislated on the subject of water saving and recovery, in some cases providing for obligations for new constructions. In other circumstances, a voluntary regime has been chosen, encouraging, with financial contributions and concessions, the application of green building principles.

2.8.2. Policies encouraging the use of ancient water tanks for modern sustainability goals

Ancient water tanks have been crucial in sustainable water management in arid and semi-arid regions for thousands of years. From the simplest holes to advanced Roman and Byzantine cisterns, they have collected and stored rainwater and aqueduct water (Mays, 2014). Ancient Indian systems like johads (earth-made check dams) and kunds (stone-lined reservoirs) have recharged groundwater efficiently and irrigated agriculture in the semi-arid regions of Rajasthan (Bhattacharya, 2015). Similarly, Roman-era cisterns in the Mediterranean, holding millions of liters of rainwater, indicate engineering prowess behind contemporary RWH designs (Mays, 2014). RWH systems also tend to have multiple uses in most cases. For instance, Gujarat's talavas (village tanks) provide water for cattle and agriculture in addition to household use, thus making communities more resilient (Sakthivadivel et al., 2004). The worth of restoring and improving such systems becomes increasingly clear when large-scale irrigation projects are costly and unfruitful. For Gujarat's desert region, village tanks (talavas) have proved promising to meet domestic water demands, and studies established how much individuals are willing to pay for their restoration (Das, 2008). Restoring such ancient water systems through local institutions can provide livelihood security and mitigate water scarcity in semi-arid regions (Sakthivadivel et al., 2004).

To date, several countries have adopted policies that encourage the use of ancient water cisterns for modern sustainability goals. n India, the Kudimaramathu Scheme, launched by Tamil Nadu in March 2017, has restored over 16,000 traditional tanks and lakes through community-led desilting and maintenance—rejuvenating groundwater levels and improving water availability (Jain at al.2014). In urban settings, China's Sponge City policy, adopted nationally since 2014, promotes the restoration and incorporation of traditional rainwater retention systems—like ponds, wetlands, and permeable surfaces—into city planning to reduce flooding, conserve water, and support resilient ecosystems (Source: Global Center on Adaptation.).

2.8.3. Legal and planning considerations for repurposing historical infrastructure

Repurposing historical infrastructure offers significant environmental, social, and economic benefits. Key challenges include:

- Ownership and Heritage Laws: Historic buildings, such as India's stepwells, are frequently protected as heritage (for example, by the Archaeological Survey of India), necessitating cooperation between water agencies and cultural authorities in order to make changes.
- Technical Adaptation: Maintaining functioning while modernizing systems such as Byzantine cisterns requires striking a balance. Although RWH design is guided by Brazil's NBR 15527 standard, retrofitting antique tanks is not covered, necessitating ad hoc solutions (Pacheco et al., 2017).

- Climate Resilience: Adaptive designs, including modular tanks or hybrid centralized-decentralized networks, are essential for long-term efficacy, even if RWH systems in southern Europe are still feasible under climate forecasts (Santos et al., 2020) (Nandi & Gonela, 2022).
- Equity in Access: Progressive subsidy programs are necessary since rural populations, including those in Texas, sometimes encounter obstacles because of exorbitant expenses (Gonela et al., 2020).

Successful repurposing requires a long-term vision, business case, and sometimes legislative changes (Finucane & Tarnowy, 2019). The process involves considering location, infrastructure type, landscape ecology, regional planning context, and regulatory frameworks (Finucane & Tarnowy, 2019). Repurposing can be seen as an evolutionary model of integrative protection, addressing shifts in social and economic contexts (Aranđelović et al., 2022). It contributes to recovering urban landscapes, fostering a sense of belonging, and promoting economic and environmental sustainability through infrastructure reuse (Stival Garrote et al., 2020). However, challenges include balancing new facilities with the preservation of historical heritage values (Aranđelović et al., 2022).

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Chapter 3

Data collection

Reliable and accurate data collection is a critical foundation for understanding and addressing water resource challenges, particularly in vulnerable island environments. This chapter outlines the methods and tools used for data collection in this study, detailing the sources, parameters, and procedures applied to gather quantitative and qualitative information relevant to water supply, demand, and infrastructure resilience. The aim is to ensure a robust and transparent evidence base to support the subsequent analysis and recommendations presented in the later chapter.

3.1. Buildings

It is essential to localize the location of roofs and identify the available surface area on them to successful rainwater harvesting. The size of the roof dictates the amount of rainwater that can be collected and harvested; larger roofs can harvest more water even in regions with low rainfall. Take accurate measurements of the horizontal projection of the roof to calculate how much water can be harvested. In addition, the knowledge of the locations of roofs enables the design of efficient conveyance systems that will transfer harvested water to storage tanks and then to the end-users. Proper identification of these parameters ensures the rainwater harvesting system is well-sized and placed for maximum efficiency in water harvesting and facilitating sustainable water management.

On the island of Ventotene, urban settlements are mostly distributed in the north and north-west part of the island, where it is possible to find settlement landscapes, as defined by the Piano Territoriale Paesaggistico Regionale (PTPR) of the Regione Lazio. The “widespread historical settlement” is present mostly along the coast, the “Historic Center” is found immediately above the port area, while the “more modern urban settlement” is in the innermost part.

In order to assess the potential for rainwater gain, in the initial step of this thesis, we import the geometry of existing buildings into QGIS. Making maps and descriptions of the buildings was therefore an essential step. The official maps of the local municipality were acquired as AutoCAD files (*.cad) in order to accomplish this purpose and get beyond the obstacle of not having ready data for QGIS software. These files included a variety of data in different fields. As a result, the necessary information related to buildings was first extracted from these files, and the unnecessary information was eliminated. The buildings' external geometry, which was in the form of polylines, was transformed into surfaces and entered into QGIS software after the unnecessary data was eliminated. Both public (Table 1) and private buildings were mapped. In order to ensure the outcome, structures' existence or absence was further confirmed using satellite maps that could be found on Google Earth (Fig. 16).

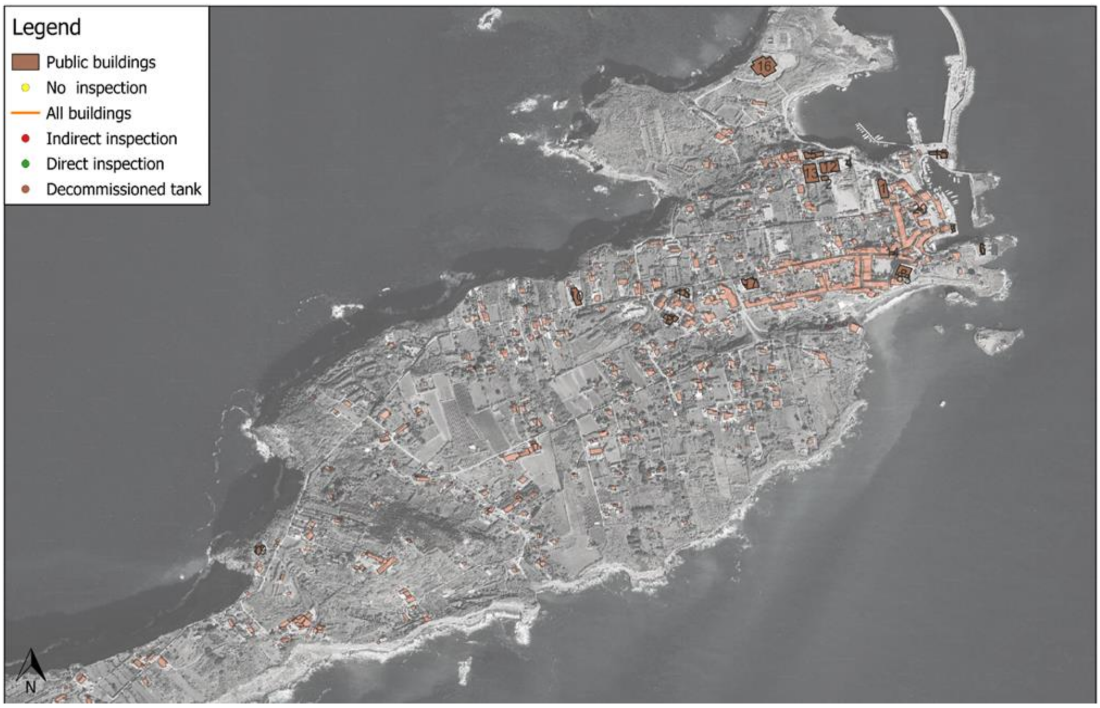


Fig 16. Maps of public and private buildings (source:author)

Table 1. List of public buildings (source:author)

	Name	Area (m^2)
1	Guardia di Finanza Comando	657.866
2	Building close to Tensostruttura	132.557
3	Municipio (Forte Torre) moat	57.489
4	Serbatoio Porto Romano	75.389
5	Centrale elettrica ENEL	413.879
6	Guardia Costiera	141.431
7	Pro-Loco Ventotene	83.299
8	Municipio (Forte Torre) main roof	550.155
9	Poliambulatorio	373.368
10	Stazione Carabinieri	516.437
11	Ecocenter	81.554
12	sala polivalente	877.62
13	Tensostruttura	1058.778
14	Italian Post Office Post	54.966
15	Stazione marittima e capitaneria di Port	332.645
16	Cimitero di Ventotene	1536.959
17	Public school	605.125
18	Case popolari	254.559
19	Museo della Migrazione e oser	204.557
20	Chiesa e oratorio	44.235
SUM		**8052.868**

Among the public buildings, the largest is the Cimitero di Ventotene (1,536.959 m²), followed by the Tensostruttura (1,058.778 m²). The smallest building is the Pharmacy (44 m²).
The total surface area of the buildings, both public and private, in Ventotene is approximately 68,390 m^2. Public buildings as surveyed and reported in Table 2 represent almost 12% of the total (Fig.17).

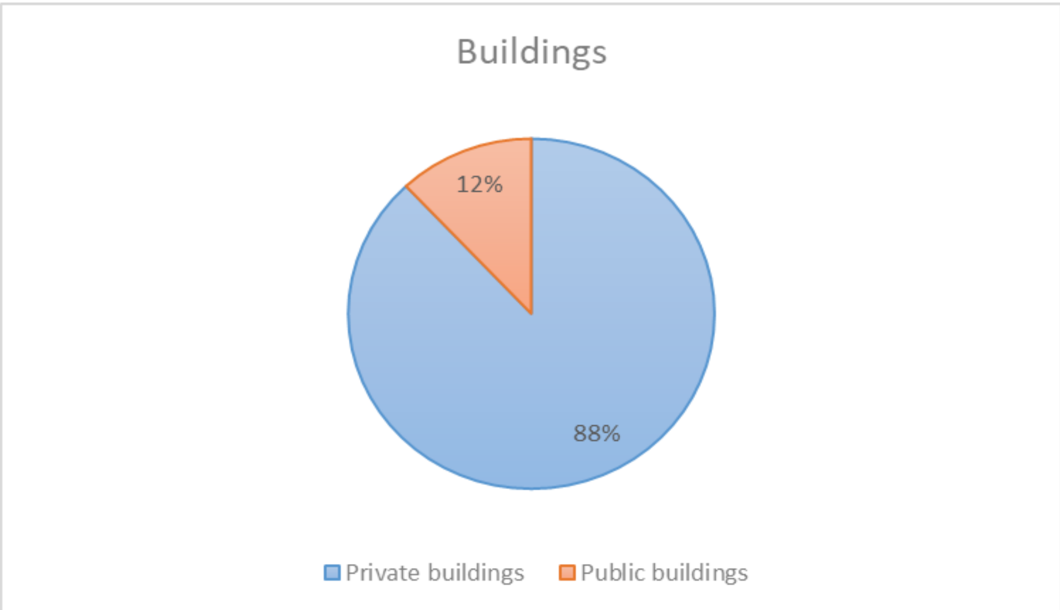


Figure 17. Percentage of buildings (source:author)

3.2. Climate

Climate study is crucial for effective rainwater harvesting as it offers valuable information in terms of patterns, frequency, and intensity of rainfall. Local climate knowledge facilitates the estimation of the probable volume of available rainwater and dictates the most suitable design and storage capacity of the harvesting system. Climate study also facilitates planning during dry periods as well as makes the system efficient and robust, which supports sustainable management of water resources.

3.2.1. Lazio region

The analysis of Lazio's climate during 1981-2010 using the E-OBS dataset shows that the Lazio region, both in terms of temperature and precipitation, has values in agreement with those obtained for central Italy (Table 2).

Table 2. Annual mean values respectively for the Lazio region, the North West area (Valle d'Aosta, Liguria, Lombardy, Piedmont), the North East area (Emilia-Romagna, Friuli-Venezia Giulia, Trentino-Alto Adige/Südtirol, Veneto), central Italy (Lazio, Marche, Tuscany, Umbria), the South (Abruzzo, Puglia, Basilicata, Calabria, Campania, Molise) and the islands (Sardinia, Sicily), of the indicators calculated from the E-OBS observation dataset for the period 1981-2010; the +/-SD column instead reports an estimate of the variability on an areal scale (through the calculation of the standard deviation). (Source: LAZIO, REGIONE PARTECIPATA E SOSTENIBILE)

	LAZIO	NORTH WEST	NORTH EAST	CENTRAL	SOUTH	ISLANDS
Average Temperature (°C)	13.7 ±2.5	9.3 ±4.8	9.7 ±4.3	13.5 ±2.0	14.1 ±2.4	15.8 ±1.5
Heating Degree Days (DD)	1987 ±697	3421 ±1575	3273 ±1380	2046 ±556	1871 ±653	1346 ±384
Cooling Degree Days (DD)	150 ±108	72 ±81	89 ±94	140 ±88	175 ±126	195 ±95
Heatwave Days (days)	3 ±1	1 ±1	2 ±2	3 ±3	3 ±3	4 ±2
Frost-Free Days (days)	2 ±5	28 ±44	24 ±37	2 ±5	5 ±5	0 ±1
Tropical Nights (days)	13 ±14	7 ±9	8 ±11	9 ±11	23 ±21	36 ±20
Frost Days (days)	35 ±30	104 ±69	101 ±59	37 ±24	24 ±27	7 ±7
Days of Intense Precipitation (days)	10 ±3	11 ±5	11 ±7	11 ±5	5 ±4	2 ±2

	LAZIO	NORTH WEST	NORTH EAST	CENTRAL	SOUTH	ISLANDS
Consecutive Dry Days (days)	43 ±9	34 ±7	33 ±4	36 ±8	49 ±11	81 ±12
3-Month Standardized Precipitation Index - Severely Dry Class (%)	5 ±1	5 ±1	5 ±1	5 ±1	4 ±1	4 ±1
3-Month Standardized Precipitation Index - Extremely Dry Class (%)	3 ±1	3 ±1	3 ±1	3 ±1	2 ±1	2 ±1
Duration Index of Warm Periods (days)	8 ±1	7 ±1	8 ±2	8 ±1	6 ±2	5 ±1
Warm/Dry Days (days)	74 ±2	76 ±5	73 ±4	74 ±2	77 ±2	81 ±2

In terms of average annual temperature, Lazio shows a value of about 14°C with a regional scale variability of about 3°C; in particular, peaks of 17°C are present above all in the west, in the Agro Pontino and Agro Romano areas. Average annual temperatures are lower (between 6 and 13°C) in the internal area of the region (on the Apennines). Even from the seasonal average temperature values (Fig. 18) it is clear that the coldest temperatures are recorded in the Apennine area that affects the eastern part of the region, while the warmest temperatures are recorded in the plains, with peaks of 25°C in summer.

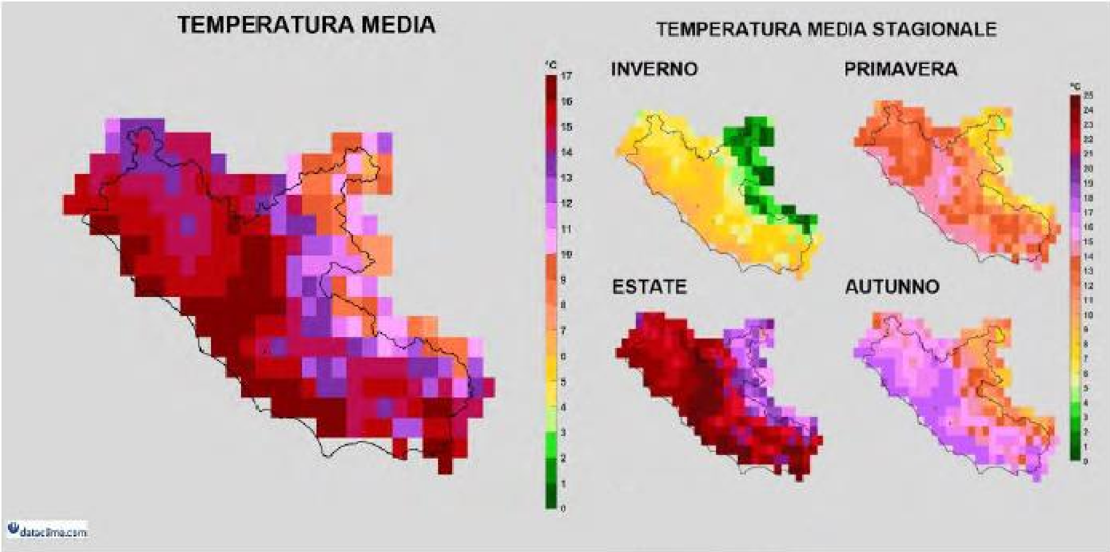


Figure 18. Maps of mean annual temperature and mean seasonal temperature [°C] (E-OBS, 1981-2010) (Source: LAZIO, REGIONE PARTECIPATA E SOSTENIBILE)

Further, Lazio is characterized by an average number of tropical nights of about 13 days: in particular, the highest number of days with high minimum temperatures is recorded in the coastal area of the region. The average number of days with frost is 35 days but on a regional scale there is a gradual increase in the number of days with minimum temperatures below 0 that goes from the west to the most internal areas of the region, with peaks of about 120 days/year in the mountainous area of the Apennines (Fig. 19).

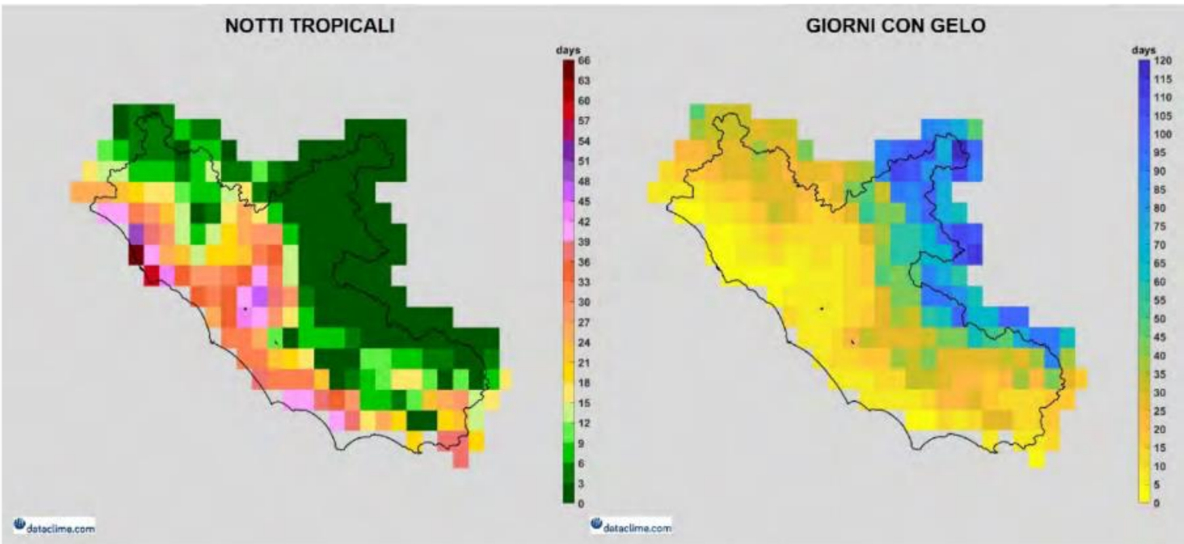


Figure 19. [Day/Year] maps of tropical nights (left) and frost days (right) (E-OBS, 1981-2010). (Source: LAZIO, REGIONE PARTECIPATA E SOSTENIBILE)

Concerning precipitation, the annual precipitation averages is around 900 mm, with the western areas receiving less rainfall compared to the internal regions (Fig. 20). An analysis for 1989-2020 using high-resolution ERA5-2km climate simulation aligns with the E-OBS dataset but amplifies some climate dynamics due to finer spatial detail.

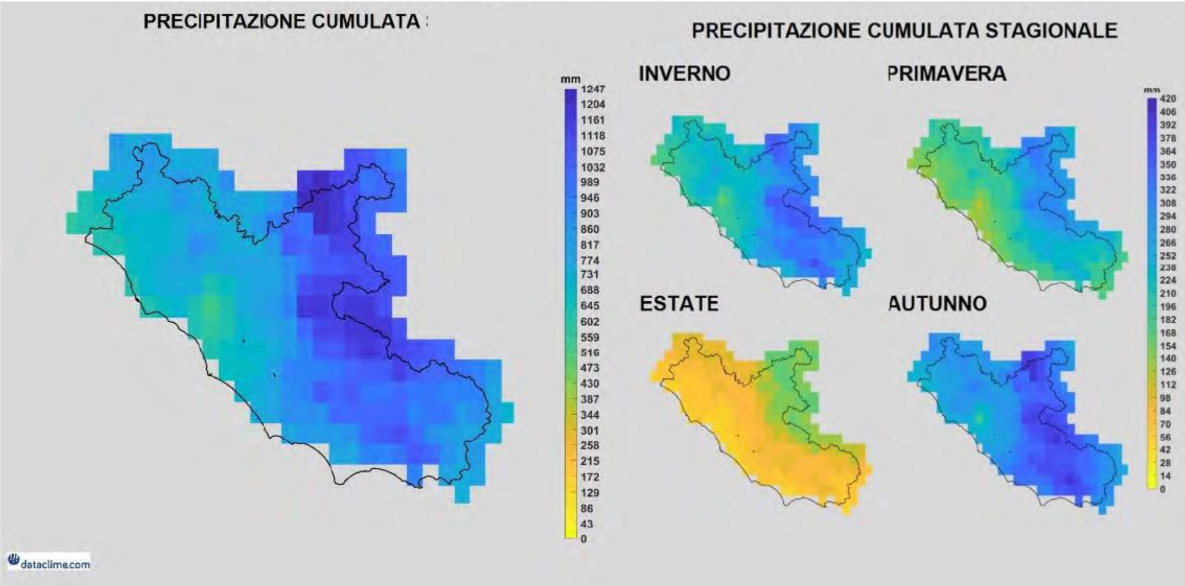


Figure 20. [mm/Year] maps Cumulative annual and seasonal precipitation (E-OBS, 1981-2010). (Source: LAZIO, REGIONE PARTECIPATA E SOSTENIBILE)

3.2.2 Pontine Islands

3.2.2.1 Temperatures and precipitation

Meteoblue's climate diagrams are available for every place on Earth and are based on hourly weather model simulations spanning 30 years. They give accurate predictions of the temperature, precipitation, wind, and sunshine as well as usual weather patterns. With a geographical resolution of only around 30 km, the simulated weather data might not accurately represent all local weather phenomena, including thunderstorms, local winds, tornadoes, and regional variations that take place in urban, hilly, or coastal regions.

As a result, the Ventotene climate and weather analysis was done on the basis of the data in Ponza, in which there is a meteorological station with an installation at 185 meters high (Campo Inglese). The island possesses a private meteorological station, which it has not been possible to consult (Source: meteoregionelazio.it). The Pontine Islands' climate is Mediterranean, with temperate and moderately rainy winters, and hot and sunny summers.

Average temperature and rainfall figures for 1991 – 2023 (climaeviaggi.it) and the last 5 years 2019 - 2023 (Regional Civil Protection Agency, Enea Processing) were compared. The mean maxima and minima during the two reference periods are given in Table 3 and Table 4. January and February are the coldest months with a mean minimum of 8 – 11 °C. It has been observed that the average minimum temperatures have increased in the past few years compared to 1991 – 2023. In general, it is noted that the minimum temperatures are high, as with small islands, where the influence of the sea is more dominant. The temperature rarely goes below zero, and only following cold spells with moderate or strong north winds, because as soon as the wind drops, the warm sea influence asserts itself again. The temperature dipped to -0.6 °C in Feb 1956, to -2 °C in Jan 1962, to -2.6 °C in Mar 1971 (record), to -0.5 °C in Mar 1987, and to -1 °C in Feb 2018. The lowest of recent five years was +4.7 °C in Jan 2019.
The highest mean temperatures are in July and August, and again, there is an increase in temperatures in the last five years. Summer, June to August, is hot and sunny with very rare rains. The temperatures are not too high for the most part, and there is a wind but there can be hot and humid periods. The dry heat of African origin is rare to come, but in the hottest periods, which are becoming more frequent, the temperature tends to reach 33/35 °C. The highest temperature on record is 37 °C, in July 1983. The highest temperature in the last five years was +34 °C in July 2023. There were over 100 summer days (i.e., maximum above 25 degrees) in the last three years (Table 4).

Table 3. Monthly Max and Min temperature 1991 – 2023 and 2019 - 2023

Months	1991 – 2023		2019 - 2023	
	Min T-MIN	Max T-MAX	Min T-MIN	Max T-MAX
Jen	9,4	12,4	10,6	13,7
Feb	8,8	12,3	11,1	14,5
Mar	10,1	14	11,6	15,3
Apr	12,1	16,5	16,8	17,3
May	15,7	20,8	16,6	21
Jun	19,6	25,1	21,4	26,2
Jul	22,3	27,7	24,4	28,8
Aug	23,1	28,5	24,3	28,9

Sep	20,4	25	22,2	26,5
Oct	17,1	21,1	18,8	22,4
Nov	116,6	17	15,5	18,9
Dic	10,5	16,6	12,8	15,9
Mean	15,5	19,6	16,8	20,4

Table 4. Max and Min temperature 2019 - 2023

Year	Counting of T->25°C	Min T-MIN	Max T-MAX
2019	112	4.7	31.9
2020	94	6.5	31.6
2021	109	5	32.7
2022	116	6.2	33
2023	114	4.9	34
2024	n.d.	8.1	24.9
Mean			

The number of days per month that reach particular temperatures is displayed in the Pontine Islands maximum temperature diagram (Fig. 21). The Pontine Islands experience a classic Mediterranean climate, with mild winters and hot summers.

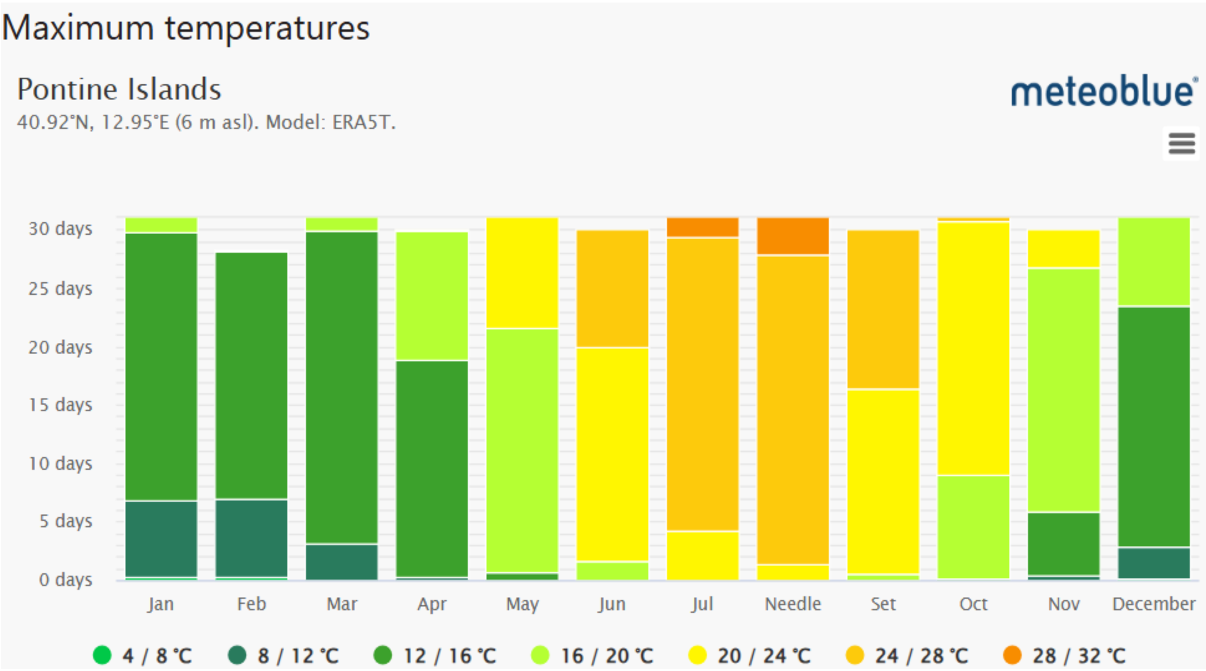


Fig 21. Maximum temperatures (source: climaeviaggi.it)

- Winter (Jan–Mar, Dec): The weather stays on the cooler side, with maximum temperatures mostly between 4°C and 16°C—perfect for those who enjoy crisp air and cozy seaside views.
- Spring (Apr–May): Temperatures slowly rise, ranging from 12°C to 20°C, making it a great time for outdoor activities before the summer heat sets in.

- Summer (Jun–Aug): The warmest months, with daytime highs reaching 24°C to 32°C—ideal for beach lovers and sun seekers.
- Autumn (Sep–Nov): A gentle cool-down, starting with warm days around 28°C in September and gradually dropping to 12°C–16°C by November.

This climate offers a balance of mild winters and sunny, vibrant summers, making the islands a tourist destination, but also offering the opportunity to implement sustainable water planning.

Precipitation is at an intermediate level. July is the least rainy month with only 1 or 2 days of rain, in which an average of 5 mm of rain fell in the period 1991 -2023 and 10 mm of rain in the last 5 years. The rainiest month is November in which it rains for about 8 - 19 days, and for which an average of 120 mm of rain was recorded in the period 1991 -2023 and 163 mm of rain in the last 5 years. The total annual precipitation was on average 665 mm in the period 1991 -2023, while in the last 5 years it reached 697 mm (Table 5 and 6).

Table 5 Annual precipitation (mm) 2019 – 2023. Stazione metereologica di Ponza.

Mese	2019	2020	2021	2022	2023
			Precipitazioni (mm)		
Gennaio	180	35	127	10	131
Febbraio	7	0	88	6	23
Marzo	9	87	39	17	25
Aprile	22	31	48	56	43
Maggio	84	34	20	10	94
Giugno	2	20	0	0	86
Luglio	18	17	0	0	15
Agosto	1	30	3	40	25
Settembre	44	69	28	227	31
Ottobre	89	44	45	66	56
Novembre	281	47,9	310	100	75
Dicembre	50,8	192,7	107	127	14
Anno	**787**	**607**	**814**	**658**	**617**

Fonte ARPC -Elab. Dati ENEA

Table 6 Day of rain 2019 – 2023. Stazione metereologica di Ponza.

Mese	2019	2020	2021	2022	2023
			Giorni di pioggia (d)		
Gennaio	19	4	19	4	18
Febbraio	3	1	13	4	4
Marzo	4	12	10	8	6
Aprile	12	6	6	9	8
Maggio	11	7	6	5	15
Giugno	3	6	2		6
Luglio	2	1		1	4
Agosto	1	3	3	6	4
Settembre	5	8	4	8	5
Ottobre	10	11	7	13	11
Novembre	27	11	26	13	13
Dicembre	10	20	16	14	10
Anno	**90**	**112**	**85**	**104**	**46**

Fonte ARPC -Elab. Dati ENEA

Fig. 22 shows the Pontine Islands' average temperatures and precipitation. The maximum daily temperature for each month is displayed by the "average daily high" (solid red line). Likewise, the average minimum temperature is shown by the "average daily minimum" (solid blue line).

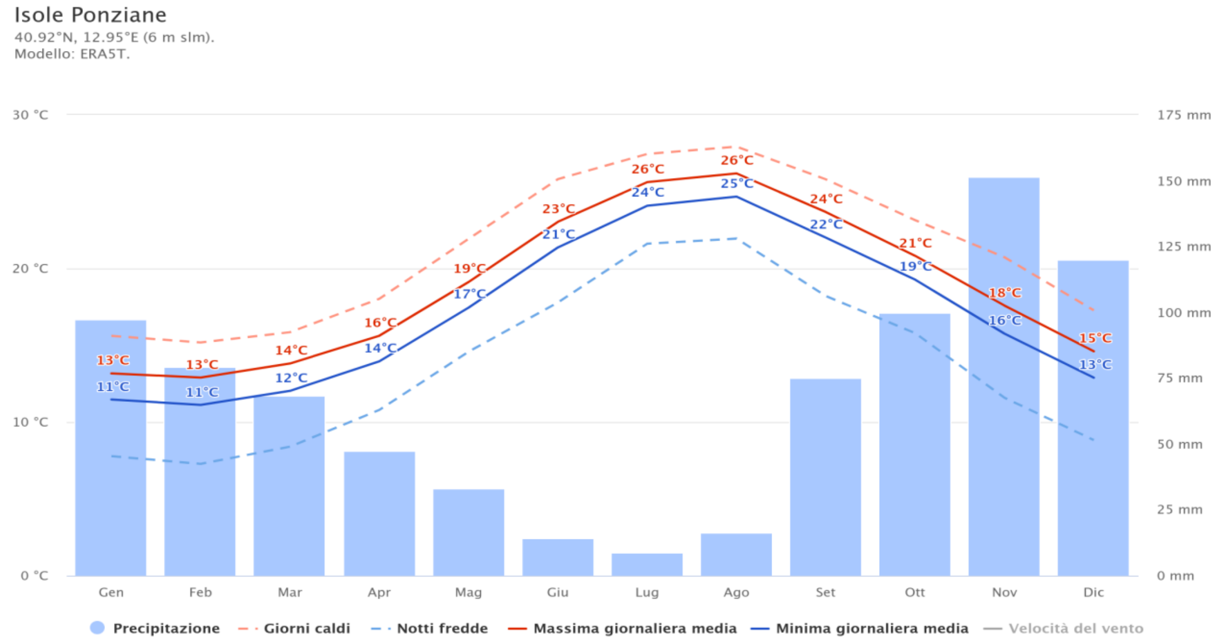


Fig 22. Average temperatures and precipitation (source: climaeviaggi.it)

The average daily high temperatures (solid red line) are highest during July and August (25–26°C) and lowest in January and February (13°C). Similarly, the average daily low temperatures (solid blue line) are 11°C in winter and 22–24°C in summer. The dashed red and blue lines represent the highs of hot days and lows of cold nights for the past 30 years and give an idea of the potential temperature fluctuations from the monthly mean.

The level of rain (blue columns) varies significantly from month to month, with higher rainfall from September to March and lower rainfall during summer (June–August). The wettest months, November, December, and January, provide best chances for water harvesting, while the dry months require serious water storage management to satisfy continuous use.

Figure 23 is the Pontine Islands rainfall chart. It is the representation of the average number of days in a month that a specified level of precipitation is attained. The Pontine Islands experience wetter winters and dry summers, typical of the Mediterranean precipitation pattern:

- Winter & Late Autumn (Oct–Mar):
    - Frequent rainfall, with some months exceeding 50 mm, and a few above 100 mm.
    - Snow is rare but possible in December and January.
    - Rain is more evenly spread across the month, with fewer completely dry days.
- Spring & Early Autumn (Apr, May, Sep):
    - Rainfall decreases, but there are still moderate showers.
    - More dry days compared to winter, though occasional heavy rain persists.
- Summer (Jun–Aug):
    - Mostly dry, with very few rainy days.
    - When rain does fall, it is usually light (< 2 mm).

- July and August are the driest months, making them ideal for outdoor activities.

These precipitation trends are essential for rainwater harvesting strategies, which could be optimized by focusing on the wetter months to store water for the dry season.

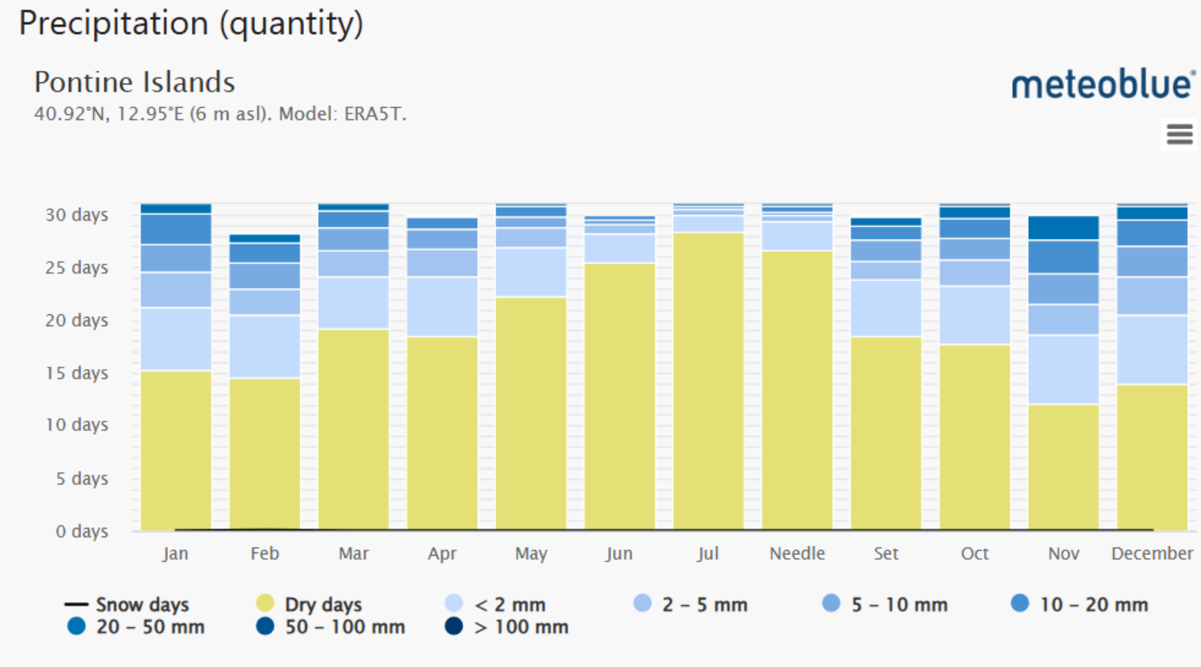


Fig 23. Precipitation (source: climaeviaggi.it)

3.2.2.2 . Cloudy, sunny, and rainy days

As it is situated near the Island of Ventotene, climatic conditions of the Pontine Islands are practically identical. Both experience cloudy wet winters and sunny dry summers (Fig. 24).

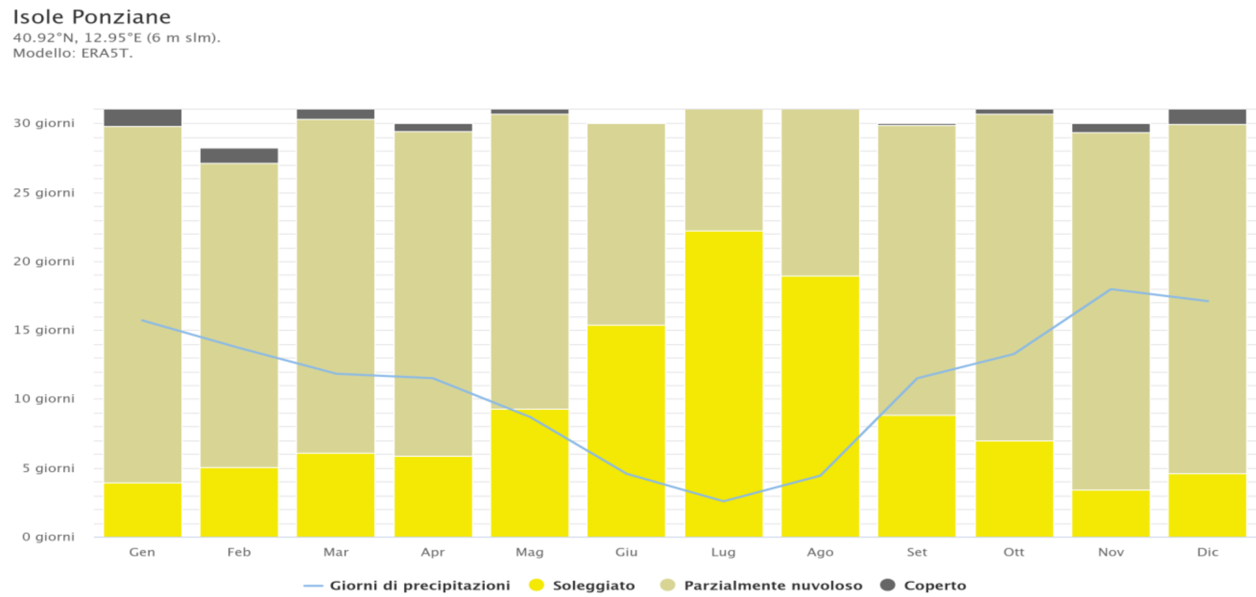


Fig 24.(source: climaeviaggi.it)

3.2.2.3 Wind speed

The days of a month when the wind reached a particular speed is shown in Figure 25. The Tibetan Plateau serves as an intriguing illustration, with the monsoon producing steady, powerful winds from December to April and gentle breezes from June to October.

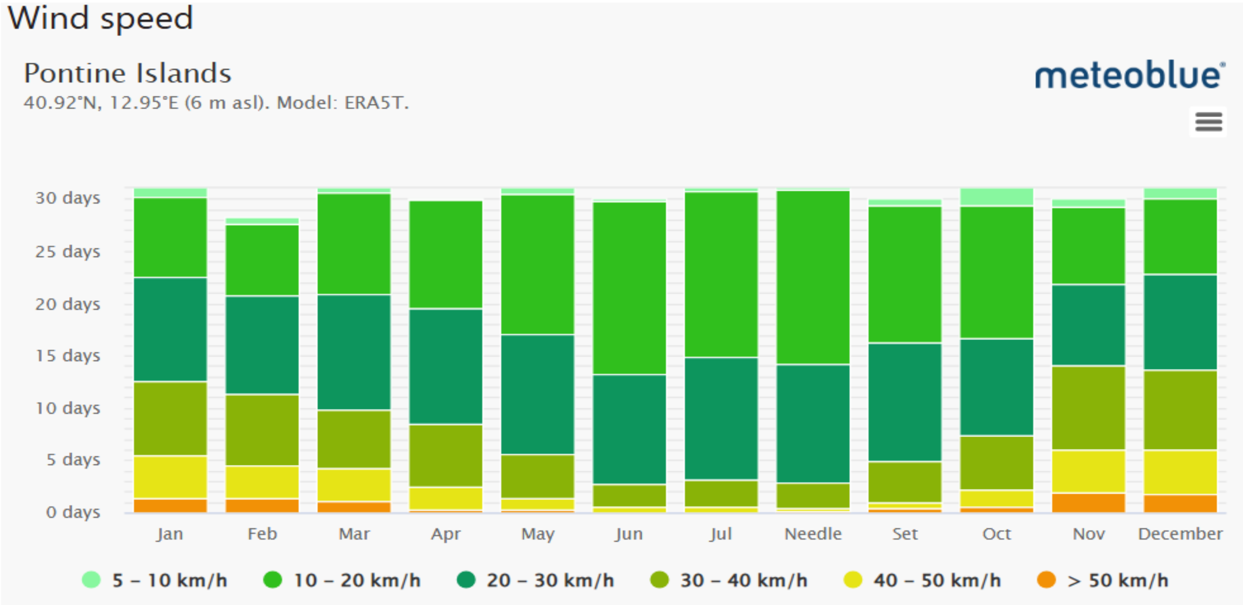


Fig 25.(source: climaeviaggi.it)

The Pontine Islands wind rise indicates the number of hours the wind blows in the specified direction each year. An example of a SW wind is one that blows from the southwest to the northeast Figure 26).

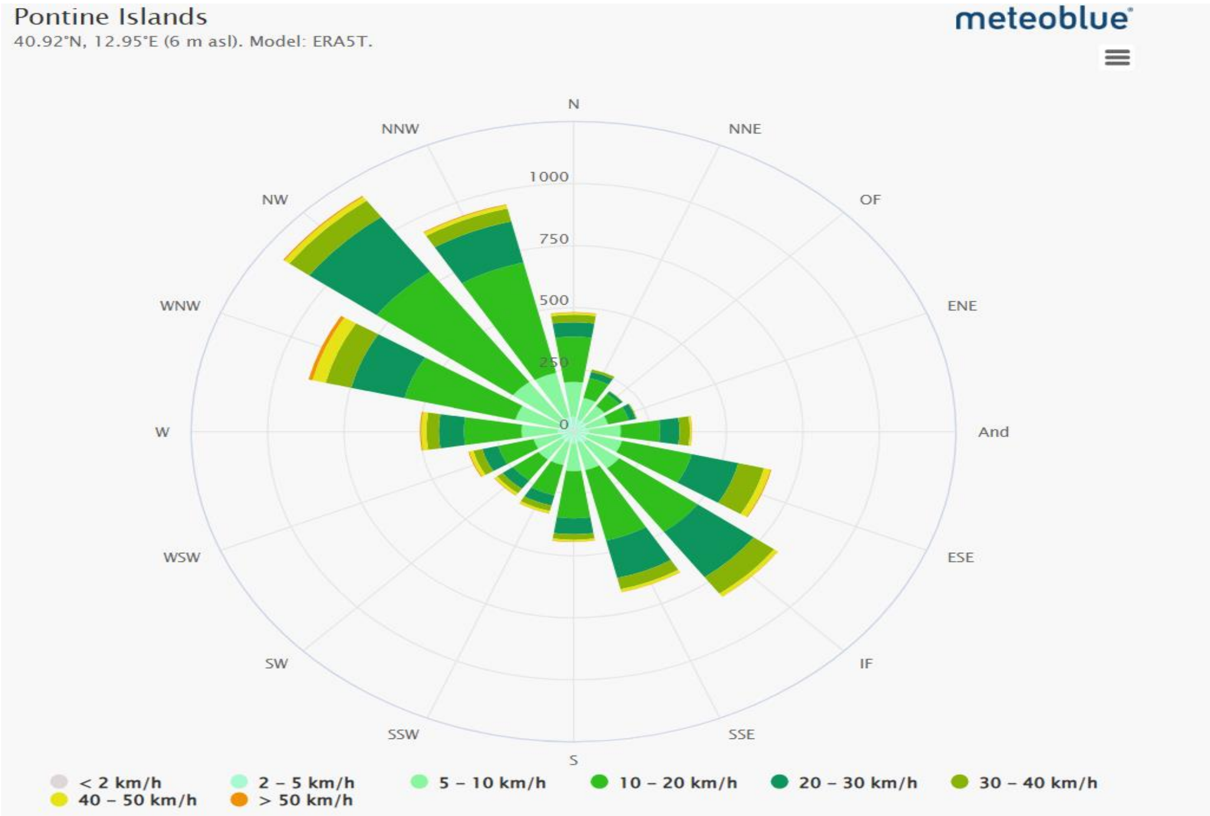


Fig 26.(source: climaeviaggi.it)

3.2.3 Future climate scenarios

The future climate projections of the indicators for Lazio region show expected shifts compared to the 1981-2010 baseline. Projections are summarized in the following tables that report the annual variations and the estimate of the associated uncertainty (through the calculation of the standard deviation) of the selected indicators respectively for the future period centered on 2030 (2016-2045) (Table 7) and for the future period centered on 2050 (2036-2065) (Table 8) (Source: LAZIO, REGIONE PARTECIPATA E SOSTENIBILE). To allow a comparison, the variations obtained for the other macro-areas of the Italian territory are also reported.

Table 7 : Annual variations for the Lazio region, the North West area (Valle d'Aosta, Liguria, Lombardy, Piedmont), the North East area (Emilia-Romagna, Friuli-Venezia Giulia, Trentino-Alto Adige/Südtirol, Veneto), central Italy (Lazio, Marche, Tuscany, Umbria), the South (Abruzzo, Puglia, Basilicata, Calabria, Campania, Molise) and the islands (Sardinia, Sicily), of the indicators analyzed for the period centered on 2030 (2016-2045); in the column +/-SD RCP4.5 (or +/-SD RCP8.5) an estimate of the uncertainty is reported (through the calculation of the standard deviation). The colors should be interpreted qualitatively: more intense colors indicate greater variations while pale colors indicate variations of lesser intensity Water demand

	VARIAZIONE CLIMATICA AL 2030s																							
	LAZIO				NORD OVEST				NORD EST				CENTRO				SUD				ISOLE			
	RCP4.5	±SD	RCP8.5	±SD	RCP4.5	±SD	RCP8.5	±SD	RCP4.5	±SD	RCP8.5	±SD	RCP4.5	±SD	RCP8.5	±SD	RCP4.5	±SD	RCP8.5	±SD	RCP4.5	±SD	RCP8.5	±SD
TEMPERATURA MEDIA (°C)	0,9	0,2	1,1	0,2	1,0	0,2	1,1	0,3	1,0	0,2	1,1	0,3	0,9	0,2	1,1	0,2	0,9	0,2	1,1	0,2	0,9	0,2	1,0	0,2
GRADI GIORNO DI RISCALDAMENTO (DD)	-212	53	-263	59	-284	70	-337	87	-267	67	-320	83	-212	54	-262	60	-202	53	-251	57	-178	38	-220	45
GRADI GIORNO DI RAFFRESCAMENTO (DD)	72	37	83	44	40	24	46	30	46	24	52	30	69	36	79	43	87	36	99	42	102	40	116	47
ONDATE DI CALDO (giorni)	3	3	3	3	2	2	2	2	2	2	2	2	3	3	3	3	3	2	4	3	4	3	4	3
GIORNI SENZA DISGELO (giorni)	-1	1	-2	1	-7	2	-8	3	-5	1	-6	2	-1	1	-2	1	-1	1	-1	1	0	0	0	0
NOTTI TROPICALI (giorni)	9	4	11	5	5	3	6	4	6	3	7	4	9	4	10	5	11	4	13	4	14	5	16	5
GIORNI CON GELO (giorni)	-8	3	-10	5	-13	3	-16	4	-12	4	-15	4	-8	4	-10	5	-6	3	-8	4	-3	2	-4	3
GIORNI DI PRECIPITAZIONI INTENSE (giorni)	0	1	0	1	0	1	1	1	0	1	1	1	0	1	0	1	0	0	0	1	0	0	0	1
GIORNI CONSECUTIVI SECCHI (giorni)	1	3	1	3	0	1	0	1	0	1	0	1	1	2	1	2	2	3	1	3	3	3	3	4
INDICE STANDARDIZZATO DI PRECIPITAZIONE 3 MESI - CLASSE SEVERAMENTE SECCA (%)	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	1	1	1	1	1	1	1	1
INDICE STANDARDIZZATO DI PRECIPITAZIONE 3 MESI - CLASSE ESTREMAMENTE SECCA (%)	2	1	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2	2	1	2	1
INDICE DI DURATA DEI PERIODI DI CALDO (giorni)	17	6	21	6	15	5	18	6	15	5	18	6	16	5	19	5	13	4	17	4	14	4	17	4
GIORNI CALDI/SECCHI (giorni)	23	8	27	10	19	8	22	9	18	7	22	8	22	8	26	9	25	8	30	9	29	11	34	12
PRECIPITAZIONE CUMULATA NEI GIORNI PIOVOSI (%)	0	6	-1	4	1	5	3	5	2	4	3	4	0	5	0	4	-1	4	-2	6	-3	4	-2	6
MASSIMA PRECIPITAZIONE IN 1 GIORNO (%)	6	5	5	5	4	3	6	4	4	5	6	3	5	4	5	5	3	4	3	5	3	4	5	7
PRECIPITAZIONE GIORNALIERA (%)	2	3	3	3	3	2	4	3	3	2	4	2	2	3	3	2	1	2	2	3	1	2	3	4
99° PERCENTILE DELLA PRECIPITAZIONE (%)	5	4	5	5	4	3	6	4	4	3	6	3	5	4	5	4	3	3	4	5	3	4	6	5

Table 8. Annual variations for the Lazio region, the North West area (Valle d'Aosta, Liguria, Lombardy, Piedmont), the North East area (Emilia-Romagna, Friuli-Venezia Giulia, Trentino-Alto Adige/Südtirol, Veneto), central Italy (Lazio, Marche, Tuscany, Umbria), the South (Abruzzo, Puglia, Basilicata, Calabria, Campania, Molise) and the islands (Sardinia, Sicily), of the indicators analyzed for the period centered on 2050 (2036-2065); in the column +/-SD RCP4.5 (or +/-SD RCP8.5) an estimate of the uncertainty is reported (through the calculation of the standard deviation). The colors should be interpreted qualitatively: more intense colors indicate greater variations while pale colors indicate variations of lesser intensity.

	VARIAZIONE CLIMATICA AL 2050s																							
	LAZIO				NORD OVEST				NORD EST				CENTRO				SUD				ISOLE			
	RCP4.5	±SD	RCP8.5	±SD	RCP4.5	±SD	RCP8.5	±SD	RCP4.5	±SD	RCP8.5	±SD	RCP4.5	±SD	RCP8.5	±SD	RCP4.5	±SD	RCP8.5	±SD	RCP4.5	±SD	RCP8.5	±SD
TEMPERATURA MEDIA (°C)	1,5	0,3	1,9	0,3	1,6	0,4	2,0	0,4	1,5	0,3	2,0	0,4	1,5	0,3	1,9	0,3	1,4	0,3	1,9	0,3	1,4	0,3	1,8	0,3
GRADI GIORNO DI RISCALDAMENTO (DD)	-337	62	-454	64	-447	93	-592	106	-422	85	-558	95	-336	62	-453	63	-319	60	-432	61	-280	45	-383	48
GRADI GIORNO DI RAFFRESCAMENTO (DD)	128	64	158	87	74	49	92	62	85	49	102	64	124	65	152	88	145	62	184	85	169	68	215	88
ONDATE DI CALDO (giorni)	6	5	7	7	4	4	4	5	4	4	5	5	6	5	7	7	6	5	8	7	7	5	9	7
GIORNI SENZA DISGELO (giorni)	-2	1	-2	1	-10	2	-13	3	-8	2	-11	2	-2	1	-2	1	-2	1	-2	1	0	0	0	0
NOTTI TROPICALI (giorni)	16	7	20	9	10	5	12	7	11	5	14	7	15	7	19	9	18	6	23	8	22	7	29	9
GIORNI CON GELO (giorni)	-13	4	-17	6	-21	4	-27	5	-19	4	-25	5	-13	5	-17	6	-10	4	-13	5	-4	3	-6	4
GIORNI DI PRECIPITAZIONI INTENSE (giorni)	0	1	1	2	0	1	1	1	0	1	1	1	0	1	1	1	0	0	0	1	0	0	0	1
GIORNI CONSECUTIVI SECCHI (giorni)	3	3	2	3	0	2	0	2	0	2	0	1	2	3	2	2	3	4	3	4	4	4	4	5
INDICE STANDARDIZZATO DI PRECIPITAZIONE 3 MESI - CLASSE SEVERAMENTE SECCA (%)	1	1	1	1	1	1	0	1	0	1	0	1	1	1	0	1	1	1	1	1	1	1	1	1
INDICE STANDARDIZZATO DI PRECIPITAZIONE 3 MESI - CLASSE ESTREMAMENTE SECCA (%)	2	2	2	2	2	2	1	2	2	2	1	2	2	2	2	1	2	1	2	1	2	1	3	1
INDICE DI DURATA DEI PERIODI DI CALDO (giorni)	32	9	45	13	26	10	38	12	26	9	36	11	28	8	40	11	24	7	35	10	25	8	39	11
GIORNI CALDI/SECCHI (giorni)	37	14	47	16	32	13	41	14	30	12	38	13	35	13	45	16	40	13	52	16	46	17	60	20
PRECIPITAZIONE CUMULATA NEI GIORNI PIOVOSI (%)	-2	4	0	5	0	5	2	4	1	4	4	4	-2	4	1	5	-2	3	-2	6	-5	4	-4	5
MASSIMA PRECIPITAZIONE IN 1 GIORNO (%)	6	6	11	7	5	4	9	3	6	4	11	5	6	5	11	7	5	5	7	6	5	6	9	7
PRECIPITAZIONE GIORNALIERA (%)	3	3	6	4	3	3	6	3	4	2	7	3	3	2	6	3	3	3	5	4	3	3	5	4
99° PERCENTILE DELLA PRECIPITAZIONE (%)	7	4	11	6	6	3	10	4	7	4	11	5	7	4	11	6	6	4	9	6	7	5	12	7

Indicator projections for the future show a general increase in average temperature for both scenarios considered (RCP4.5 and RCP8.5), more pronounced in the medium-term period (2050s) and considering the RCP8.5 scenario, with an increase of up to 1.9 °C. These values are in agreement with those expected for the different macro-areas of the national territory.

Climate projections show a general reduction in periods with very cold days, i.e. with maximum and minimum temperatures below 0 °C (Days without thaw and Days with frost) throughout Lazio, with more pronounced variations according to the RCP8.5 scenario. On the contrary, for periods with days with high temperatures (Heat waves, Tropical nights, Index of duration of hot periods, Hot/dry days), a general increase is expected that affects the entire region, more pronounced than expected for the entire central Italian area, with more substantial variations in the medium-term period (2050s) and considering the RCP8.5 scenario.

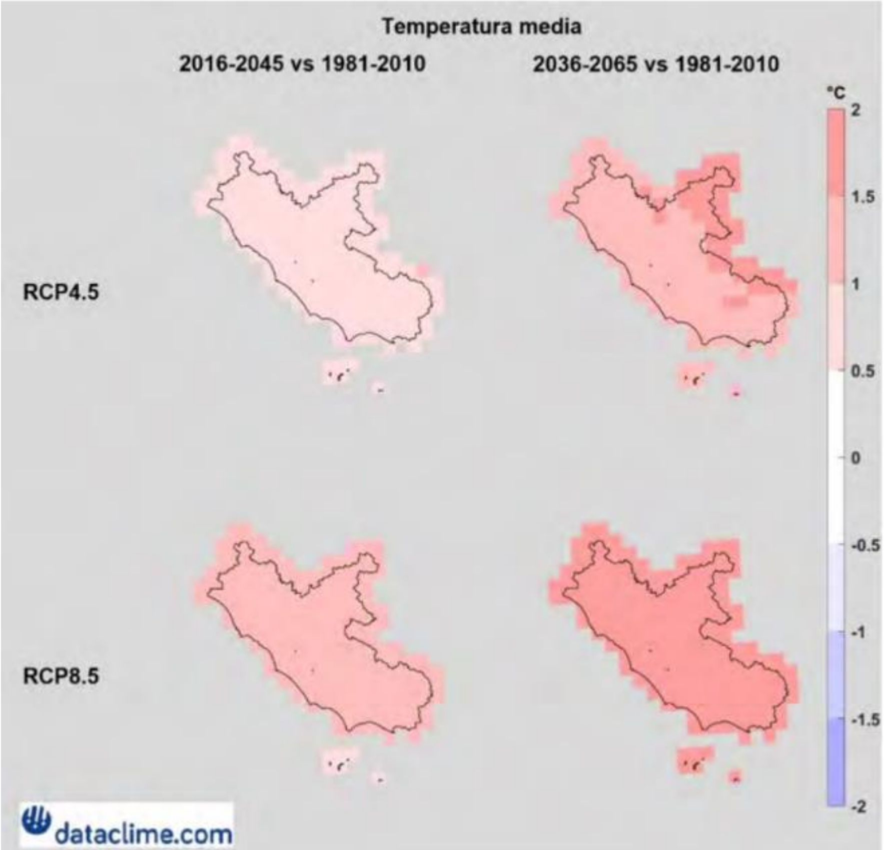


Figure 27. Climate changes in mean temperature [°C] for the periods 2016-2045 (left column) and 2036-2065 (right column), compared to the reference period 1981-2010, according to the RCP 4.5 (top row) and RCP 8.5 (bottom row) scenarios considering the EURO-CORDEX model ensemble.

3.3. Water storages

A large variety of operational, decommissioned, and unconfirmed reservoirs are part of the storage system of the island of Ventotene are found in Ventotene's water storage tanks, highlighting the potential and difficulties of using these facilities for sustainable water management. Many of them are Roman cisterns of large volumes, used the by Bourbons mainly in correspondence with the inhabited center. Over the years, many projects have been carried out, aimed at the survey, consolidation, and enhancement of these cavities, which have led to a fairly clear knowledge of the cavities present.

In the framework of the Green Islands Programme, the municipality of Ventotene with the support of ENEA, new inspections of the principal cisterns present in the inhabited center has conducted, which results are reported in the following Figure and table (Geores srl) (Fig. 28, Table 9). More specifically, the investigation was carried out in order to define the geometry, the accesses, the presence of any damages in order to verify the actual functionality of the tanks being investigated. This activity was preparatory to a possible intervention for the functional reuse of the tanks by the Municipal Administration.
Two type of inspection have been carried out:

1. direct inspections in the tanks with specialized personnel descending directly into the tanks to operate in confined environments, with specific equipment for environmental monitoring and for the summary measurement of volumes;
2. indirect inspections, from the well mouth without descending inside, in the underground tanks

.
The largest tank, with a capacity of approximately 300 m³, is the Porto Romano Tank. Originally a Roman cistern, it was later incorporated into a building and used by the Bourbons in the 18th century, during the Fascist era, and, more recently, by the operator of the integrated water service as a storage tank for water brought in by ship. It is currently deactivated and cannot be used. Other noteworthy storage facilities, such as Santa Candida (160 m³), Piazza Castello (160 m³), Municipio Forte Torre (140 m³), Via Roma (130 m³), and Via Granili (130 m³), continue to be important resources, albeit some need to have their operating status confirmed. Furthermore, a number of tanks have been identified but not directly inspected, leaving their volume and condition unknown.

Regarding state of conservation (S.O.C.), Porto Romano, Santa Candida, Municipio Forte Torre, and Piazza Castello are classified as "excellent", meaning they are well-maintained and fully operational. On the contrary, tanks like Via Roma, Porto Romano, Località Belvedere, and Via Granili require further inspection, as their structural integrity and functionality remain uncertain..

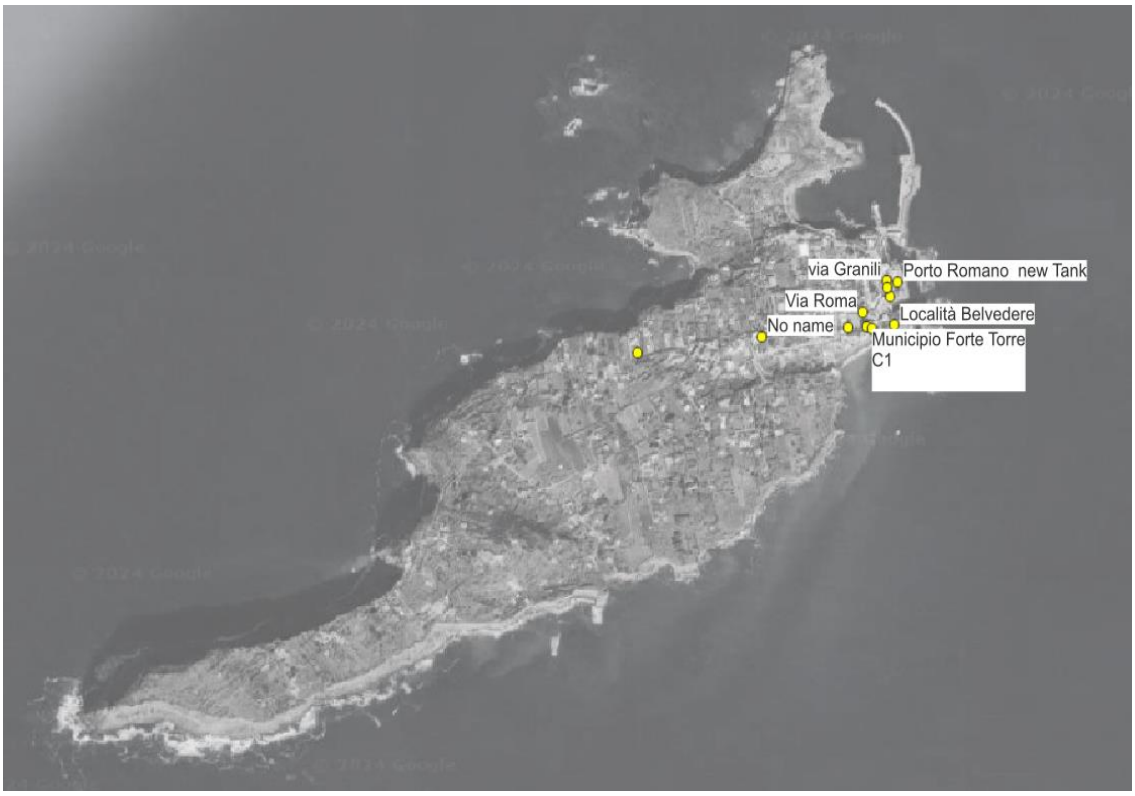
From an historical typology perspective, the cisterns taken into consideration were traced back to homogeneous groups by the period of construction and use. It can be distinguished:

- cisterns and aqueducts of the imperial age (Roman era), not affected by major uses in the Bourbon era (Via Porto Romano - Pozzillo, Via Roma, Via Granili, Località Belvedere);
- cisterns of the imperial age but adequate in Bourbon era, contemporary with the construction of the Castle, the Piazza and the Church of Santa Candida (Forte Torre, Santa Candida, Piazza Castello);

- ancient tanks already reused in modern times (Porto Romano).

Bourbon-era tanks and modern ones (Santa Candida, Forte Torre, Piazza Castello, Porto Romano) appear to be better preserved, possibly due to more recent use and renovation. In contrast, Roman-era tanks (via Roma, Via Granili) show signs of degradation, likely resulting from centuries of wear. Some tanks lack historical classification, indicating gaps in documentation that require further research.

In terms of inspection methods, direct assessments have been conducted on Santa Candida, Municipio Forte Torre, Porto Romano and Piazza Castello, confirming their good condition. However, Via Roma, Località Belvedere, Via Granili, and Porto Romano New Tank were only assessed indirectly, meaning their exact conditions remain uncertain and require additional field verification.



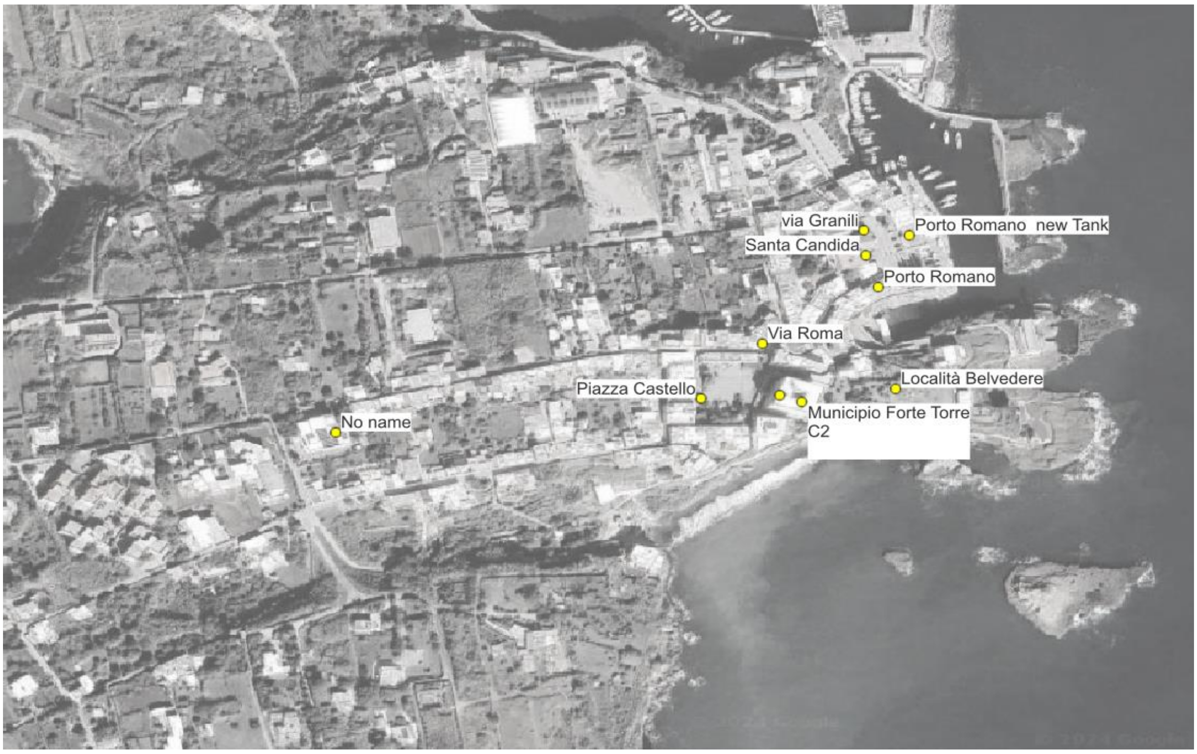


Figure 28. Location of storages in island (Source:Author)

Table 9. Data of each water storage (Source:Author)

ID	Name	Max Volume (m^3)	S.O.C.	Typology	Inspection Type
1	Santa Candida	160	Excellent	Bourbon	Direct
2	Via Roma	130	To be verified	Bourbon	Indirect
3	Porto Romano	0	To be verified	Roman	-
4	Località Belvedere	0	To be verified	-	Indirect
5	No data available	0	-	-	-
6	Porto Romano New Tank	300	Decommissioned	Decommissioned	Indirect
7	Municipio Forte Torre	140	Excellent	-	Direct
C1	No data available	-	-	-	-
8	Piazza Castello	160	Excellent	Bourbon	Direct
10	Via Granili	130	To be verified	Roman	Indirect

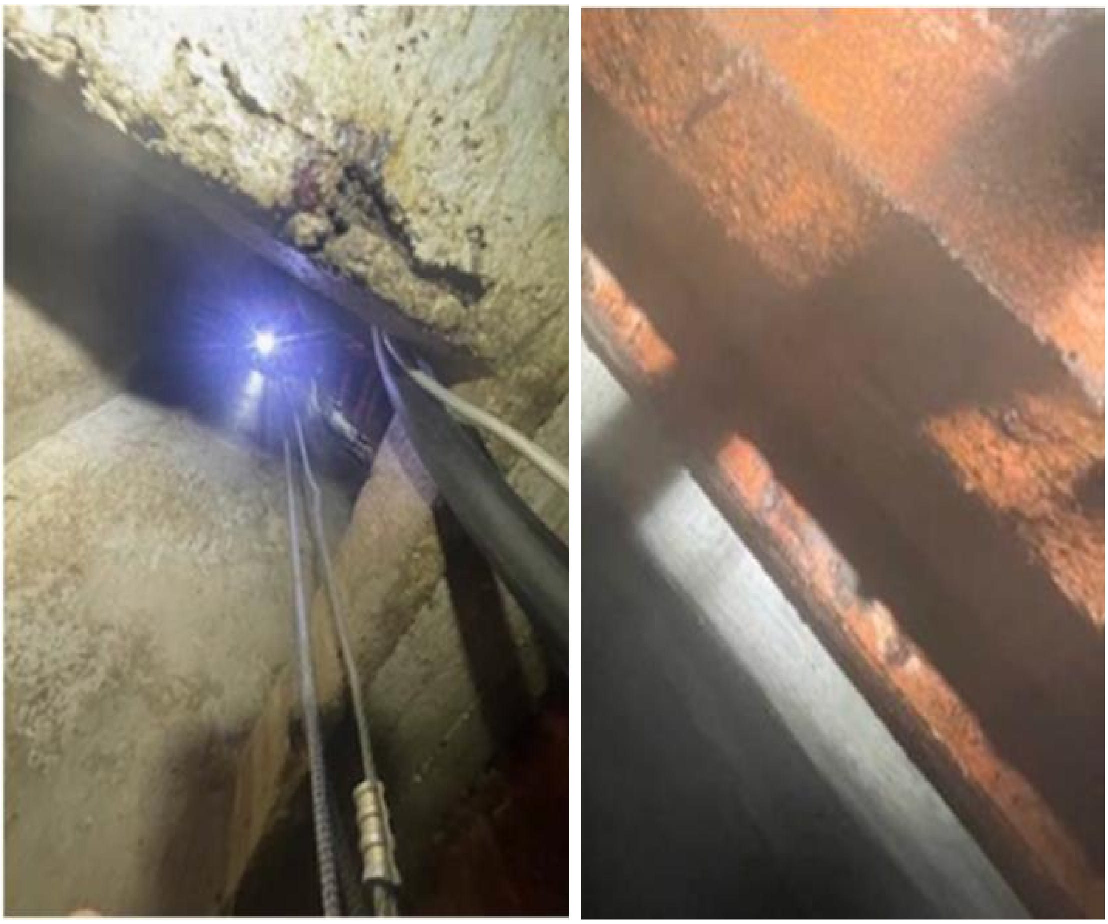
3.4 Case study – Central cistern Forte Torre

For the purpose of this thesis, an ancient tank was considered to be re-functionalized. Based on the exploration done, depending on the state of conservation of the cisterns, proximity to collection areas easily accessible and water needs, the central cistern of Forte Torre was chosen upon which several scenarios were developed. It was also evaluated as far as its historical, cultural, and architectural interest was concerned. Built in the 18th century, Forte Torre served as a defensive fortification and as a central point of governance in the Bourbon period. Its elevated position and unique architecture made it an observable landmark, and it remains so even today. Over time, Forte Torre has represented the nature and tradition of Ventotene in capturing its strategic position as a place, historical richness, and strength of its people. Besides, the cistern underneath it was part of the roman aqueduct. Today, the historic Forte Torre has been repurposed to serve as the municipal headquarters of Ventotene, blending its centuries-old architectural heritage with contemporary administrative functions.

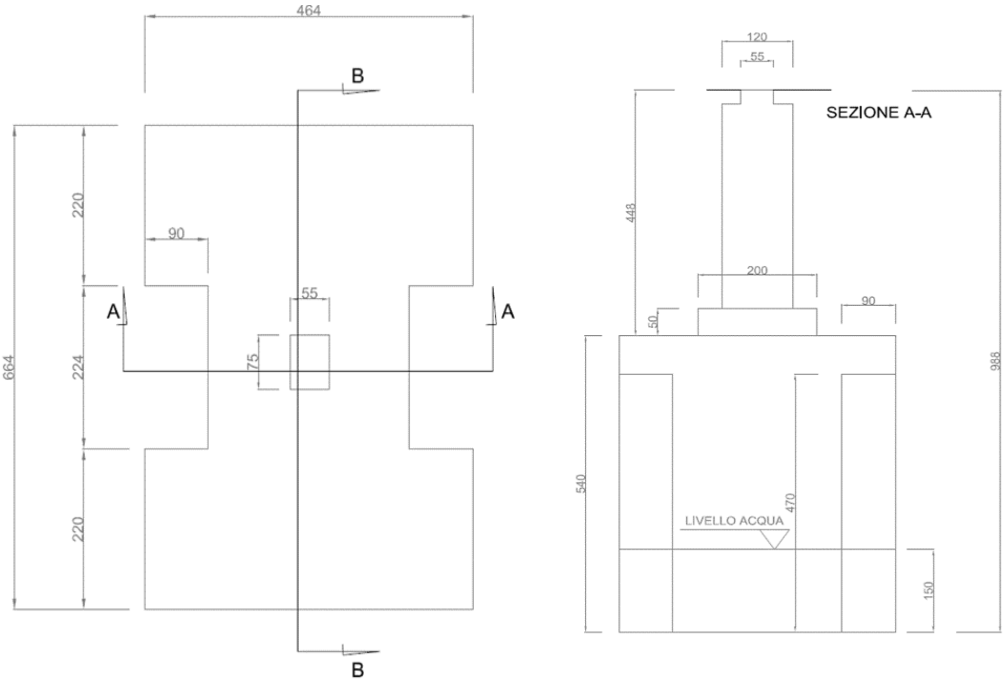
The ancient hydraulic water storage, well and cistern, is incorporated in the Forte Torre (Town Hall) basements. Specifically, access is inserted in the storage room already present for the Museum's archaeological artifacts. Located conveniently in front of Piazza Castello, the cistern was initially excavated during roman times directly into the island's pyroclastic material. Bourbonic restoration involved significant changes in the form of the addition of concrete vertical walls, whereas recent restoration includes support slabs and the installation of iron stairs for easy access (Figure 29).

Access into the cistern is through a single entrance with a vertical well at ground level. The well opening is highly protected by a rectangular metallic cover measuring approximately 75x55 cm. The well is cylindrical with a circular base diameter of 0.55 meters. The well descends a few centimeters below the ground surface before it becomes square in shape, 1.2 meters by 1.2 meters, with a depth of 4.48 meters.

The cistern is an H-shaped one, formed by two projecting internal walls which bisect the room (Figure 30). One side of the cistern measures 4.64 meters, and the other side, which has these projecting walls, stretches to 6.64 meters. The overall height of the cistern is 5.40 meters.



.Figure 29 Images of water storage (source: ENEA)



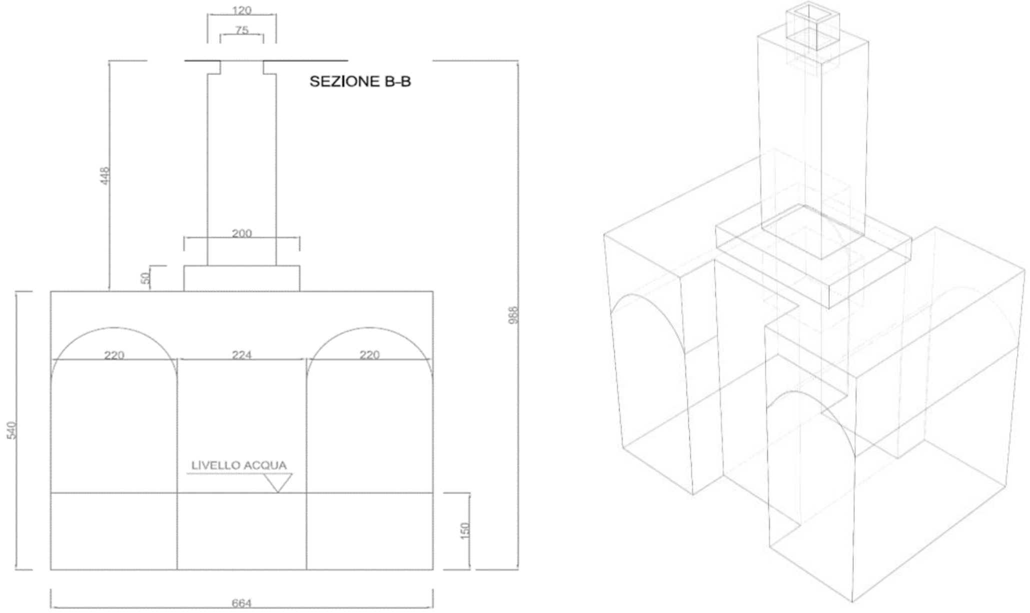


Figure 30. Plans of water storage (source: ENEA and author)

3.5. Water demand

Determining water demand is essential for effective rainwater harvesting, as it allows for the design of systems that are appropriately sized to meet actual needs. Understanding consumption patterns ensures that the collected rainwater is used efficiently, reduces reliance on external water sources, and enhances the sustainability and resilience of local water management.

For this purpose, the estimation of building water requirements is calculated through two approaches. The first is a top-down estimation, which calculates the total water consumption of the community and determines the average per capita water consumption. The second approach, using field data collected by ENEA, evaluates the building's water usage potential by analyzing the building and the number of its users to estimate the water requirements of the building. The data required to develop both approaches are presented in the following paragraphs.3.5.1. Top-down estimation

Drinking water in Ventotene is supplied by ship tankers and drinking water produced by the desalination plant.

Figure 31 shows the quantities of drinking water produced by the desalination plant and/or transported by tankers and fed into the water network.

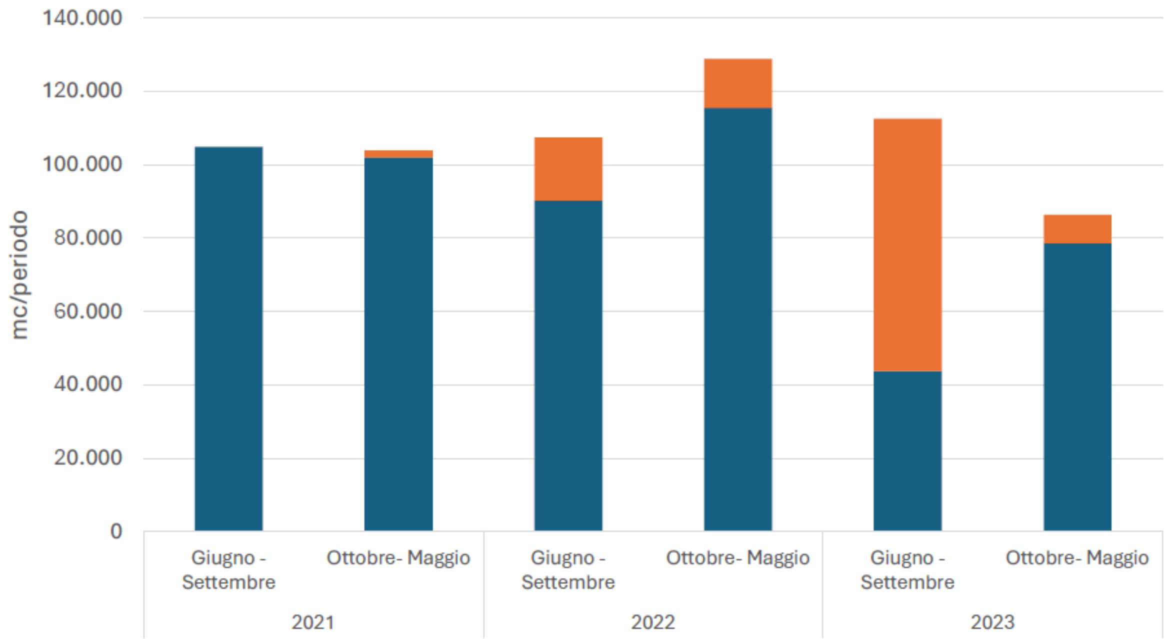


Figure 31. Drinking water supply data via desalination plant and/or ship tankers annual detail – Period 2021 – 2024. (ENEA). Orange bar: ship tankers ; blue bar: desalination plant

These figures highlight the island's high dependency on external water sources, particularly during the tourist season.

The daily water consumption per inhabitants has been calculated considering the volume fed into the water network, the losses in the water network and the served inhabitants.
Ventotene water network is characterized by high water losses (60 - 90%), primarily due to the island's aging infrastructure and the complexity of water distribution systems. These losses significantly impact the efficiency of water supply (Battistelli et al., 2024). Further considering the few small inhabitant resident population during the off-season (October to May) of approximately 350 people, and the summer peak, when the population swells to around 2,750 people, per capita water consumption can be estimated to be equal to 500 L/ab/d during the off-season and 135 L/ab/d during the summer season, respectively.

More in detail the quantities of drinking water fed into the water network, together with the water network loss, the served inhabitant and the calculated per capita water consumption (L/Ab/d) are reported in Table 10.

Table 10. Details the quantities of drinking water

Period	Volume fed into the water network (2021 -2023) m3/period	Loss water network %*	Served Inhabitants	per capita water consumption (L/Ab/d)
June-September	105.000 – 115.000	60	2700	135
October- May	85.000 – 130.000	60	350	511
Annual	200.000 – 240.000	60	1133	215

3.5.2. Forte Torre water usage potential

Forte Torre is a large-scale civil structure with extensive spaces hosting activities with varying water requirements. Assessing the water demands within a public building is noted to be a complex operation, as it involves diverse user categories and uses that change over time and space. The complexity is further increased by the presence of areas dedicated to different activities (Puclic offices, Museum, and Residential Services), which are utilized differently during various periods of the year.
As a result, the water consumption of Forte Torre was evaluated in this thesis by estimating water requirements based on various uses, referring to data from literature sources. To achieve this, it was necessary to implement a methodology that included:

- Identifying and quantifying the types of users present within the structure, according to the activities described previously.
- Collecting and processing qualitative and quantitative information related to the water consumption of each type of user.

Regarding the first point, following discussions with ENEA, which conducted several site inspections, it was possible to identify the activities present in Forte Torre on each floor. Currently, Forte Torre houses the Municipality, the Marine Reserve, the Archaeological Museum, and also includes 5 residential apartments. The details are provided in the following Table11.

It is clear from the study that Forte Torre has ten restrooms spread throughout the building's common and private areas. The majority of faucets are of the conventional variety, which means they do not include dual-action mechanisms or timing. The toilet tanks have a single flush system, with an estimated consumption of approximately 10 liters per flush, as the bathrooms were constructed some time ago.

Table 11. Details of the Forte Torre

Building	Floor	Activity	Details
Forte Torre	Ground floor	Archaeological museum	Equipped with 1 disabled-accessible restroom
	Mezzanine	Marine booking offices, social aid office, shared rooms	Equipped with 2 restrooms
	First floor	Municipality offices, council hall	Equipped with 2 restrooms
	Second floor	5 residential apartments, archive	

Based on the methodology, the following categories of users were identified and classified:

- **Office**: Includes technical/administrative offices of the municipality, as well as the offices of the Archaeological Museum, Marine Reserve, and Social Assistance. Their estimated water consumption is linked to restroom usage.
- **Tourist**: Refers to tourists visiting the Archaeological Museum, with estimated water consumption associated with restroom usage.
- **Domestic**: Includes the residential accommodations on the second floor of Forte Torre, where estimated water consumption pertains to domestic activities (kitchen, shower, WC, personal hygiene, etc.).

All the identified user categories (“office,” “tourist,” and “domestic”) can be considered functional "common" categories, where activities involve known water uses of a civil nature (toilet flushing, showering, personal hygiene, etc.) and are quantifiable based on estimates derived from data of similar user groups.

Table 12 presents the types of water users identified, along with notes on the number of users and their presence in the buildings.

Table 12. Types of water users identified

Building	Activity	User Type	Daily Users	Presence Notes
Forte Torre	Archaeological Museum	Tourist	7	April–September 2024: 1078 visitors; 2023: 1366 visitors; Avg: 1222
	Archaeological Museum Office	Office	1	8 hours/day from April to September
	Social Assistance Offices	Office	1	36 hours/week, averaging 7.2 hours/day
	Marine Reserve Offices	Office	3	36 hours/week, averaging 7.2 hours/day
	Municipal Offices (Permanent and Temporary Employees)	Office	7	36 hours/week, averaging 7.2 hours/day
	Council Chamber (Politicians)	Office	1	Estimated avg presence: 1 politician/day for 8 hours
	Apartments	Residential	5	1 person/apartment

For the purpose of calculating the annual water requirement, the daily usage data was assessed on an annual basis. Calculations are reported in Chapter 4.

3.6. Conclusion

The data presented in this chapter highlight the significant potential of Ventotene in terms of its ancient water tanks, that can be repurposed to collect rainwater. Further, the Pontine Islands' climate presents opportunities for rainwater harvesting, with wet months (September–March) ideal for collection and dry summers requiring efficient storage. Implementing climate-adaptive urban planning, water-efficient buildings, and advanced RWH systems can enhance water resilience and sustainability, helping the region adapt to climate challenges.

More in details, the temperature patterns have important implications for water management and urban sustainability:

- Higher summer temperatures (June–August) increase evaporation rates, requiring efficient storage solutions such as covered or underground reservoirs to minimize water loss.
- Colder winter nights (December–February) provide better water retention conditions, making this season ideal for maximizing rainwater collection and storage.

To enhance the efficiency of rainwater harvesting (RWH) systems, several strategies should be considered:

- Maximizing rainwater collection in autumn and winter to ensure sufficient supply for dry months.
- Reducing evaporation losses by using shaded, covered, or underground storage systems.
- Buildings and urban infrastructure should be designed with climate-adaptive materials to ensure thermal efficiency and reduce energy consumption
- Implementing water-efficient urban planning, including green roofs, permeable surfaces, and decentralized water storage facilities to support sustainable water management.

The necessity for climate-resilient infrastructure is further highlighted by the 30-year climatic patterns, which indicate rising temperature and precipitation variability. Adaptive water storage technologies, rainwater harvesting, energy-efficient buildings, sustainable urban landscapes, together with desalination technologies are essential to improve water security since future climate change may exacerbate seasonal differences. Additionally, optimizing water distribution and minimizing transport losses could significantly improve per capita supply.

Furthermore, municipal laws and policies should encourage the use of RWH, encouraging public buildings, residential neighborhoods, and business sectors to employ rainwater collection and conservation techniques when water scarcity becomes a critical concern.

Addressing these challenges is crucial for Ventotene’s long-term sustainability, especially as climate change and increasing tourism exert additional pressure on its fragile water resources.

Chapter 4.
Methodology and Analyze

Within this chapter, the methodological framework adopted for the study is outlined, followed by a detailed analysis of the collected data. The first section describes the tools, techniques, and procedures used for data collection. The second section presents the analysis of the data for the study of Forte Torre Tank, aiming to evaluate the potential of the ancient water system in ancient era and assess the feasibility of its integration into a modern sustainability strategy.

4.1. Research Design and Approach

Like many regions worldwide, Ventotene Island faces challenges in water resource management due to climate change-induced variability. The increasing strain on traditional water supplies necessitates alternative strategies, with RWH in urban settings emerging as a viable solution. Historically, Ventotene was equipped with rainwater collection tanks, constructed during the Roman and Bourbon periods, which played a crucial role in the island's water infrastructure. However, their current condition, storage potential, and feasibility for reuse remain largely unexplored.

This research employs a mixed-methods approach, combining geospatial analysis, hydrological modeling, and historical site evaluation to assess the potential for repurposing these ancient storage systems.

The study follows a systematic methodology involving:

I. Geospatial Analysis using GIS
   - mapping the exact locations and characteristics of the ancient tanks.
   - Evaluating land topography, catchment areas, and surface runoff dynamics to determine potential RWH efficiency.

II. Hydraulic Simulation with SWMM
   - Analyzing past and present hydraulic conditions to estimate how these tanks functioned historically and their potential for future use.

III. Field Surveys and Infrastructure Assessment
   - On-site inspections by speleologist of tank structures, accessibility, and potential restoration needs by technician.
   - Integration of historical records and municipal data to understand past usage and maintenance practices.

IV. Comparative Evaluation of Past *vs*. Present Water Management Practices
   - Assessing how historical engineering principles can be integrated into contemporary urban water solutions for increased resilience.

This structured approach enables a comprehensive understanding of how Ventotene's ancient water storage systems can be adapted to mitigate modern water scarcity, providing both historical insights and practical recommendations for sustainable urban water management.

4.2. Data Collection

Primary data were collected through on-site field assessments in Ventotene, focusing on the following key aspects:

4.2.1. Tank Volume, Structural Integrity and Geographic Positioning

Measurements of water storage capacity, current condition, and accessibility of ancient reservoirs were evaluated. GPS mapping was used to pinpoint locations of rainwater collection sites and assess their connectivity to buildings. The exact locations of the ancient tanks have been mapped, along with their key characteristics (Table 13), and all the information has been integrated into QGIS (Fig. 32).

Table 13. coordination of water storage

Name	Min_volume	Max_Volume	x	y
Via Roma	120	130	13.43259	40.79673
Porto Romano	0	0	13.43344	40.79716
	0	0	13.42562	40.79563
Località Belvedere	0	0	13.43357	40.79639
Porto Romano new Tank	300	300	13.43367	40.79755
via Granili	120	130	13.43334	40.79759
Municipio Forte Torre	140	140	13.43272	40.79634
Piazza Castello	160	160	13.43214	40.79632
No name	0	0	13.42947	40.79606
Santa Candida	160	160	13.43335	40.7974
Municipio Forte Torre	0	0	13.43288	40.79629

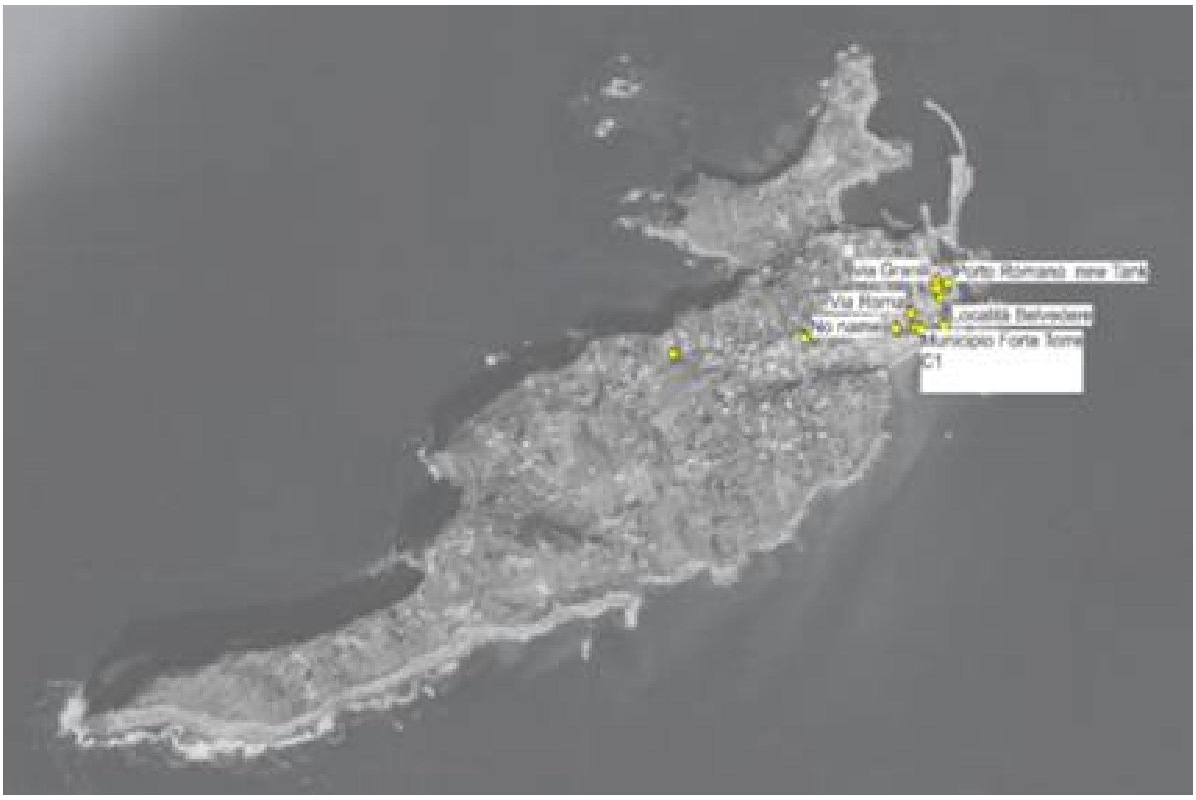


Figure 32. Location of water storage

4.2.2. Public buildings locations and catchment areas

The exact locations of each public building have been mapped, along with their catchment areas, as reported in chapter 3 (Table 1). All the information has been integrated into QGIS (Fig. 323).

Fig 33. Maps of public and private buildings, and Case Study (source:author)

4.2.3. Water demand in the past and nowadays

4.2.3.1. Water demand in the past

Water consumption in ancient societies, particularly in the Roman Empire, remains a compelling subject for researchers. Despite the scarcity of direct data, a combination of archaeological evidence, historical texts, and comparative studies allows for plausible estimates of daily water use. This study focuses on Roman soldiers in Italy approximately 2,000 years ago and proposes a range of 7 to 18 liters of water per person per day, contextualizing the logistical and environmental factors that shaped these figures.

The estimation of water consumption in ancient societies relies on three primary sources:

- Archaeological Evidence: Roman hydraulic infrastructure, such as aqueducts, water storage basins in military camps (castra), and transport vessels like amphorae (Hodge, 2002).
- Historical Texts: Descriptions by Roman authors such as Vitruvius in De Architectura (Book VIII), which detail standards for wells and aqueducts.
- Comparative Studies: Analogies with traditional communities lacking modern plumbing systems (Roth, 1999).

The daily water consumption of Roman soldiers can be divided into four categories as reported in Table 14.

Table 14. Different use of water in ancient time

Drinking Water	The physiological need for drinking water under normal conditions is 2–4 liters per day, but for soldiers in hot climates or during strenuous activities, this could rise to 3–5 liters (WHO, 2004).
Cooking	The soldiers' diet—comprising bread, legumes, and meat—required 1–3 liters of water daily for preparation. Archaeological finds of cooking pots in Roman forts (e.g., Vindolanda in Britain) corroborate this estimate (Bowman, 2003).
Personal Hygiene	While public baths (thermae) were common in Roman cities, soldiers in frontier camps had limited facilities. Evidence from latrines and washbasins in military forts suggests 1–2 liters per day for basic hygiene (Keppie, 1984).
Secondary Uses	Washing clothing, equipment, or supplying water to horses (requiring 20–30 liters per horse daily) also contributed to consumption. During campaigns, however, such uses were often minimized.

Roman engineering, particularly aqueducts, revolutionized water access in cities and military camps. For example, the Aqua Claudia aqueduct (completed in 52 CE) delivered approximately 184,000 cubic meters of water daily to Rome (Aldrete, 2007). Assuming a population of 1 million, this equates to ~184 liters per capita daily, though this figure includes public uses (baths, fountains). Personal consumption likely ranged between 20–50 liters.

In contrast, soldiers stationed in frontier regions (e.g., Germania) relied on wells or rivers. The capacity of leather water carriers (utres)—typically 1–2 liters—suggests that during water shortages, daily intake might drop to 5 liters (Roth, 1999). In addition there are some factors that impact on the water consumption:

- Climate: Consumption in arid southern Italy exceeded that in the humid north.
- Resource Access: Permanent forts) had deep wells, while temporary camps depended on surface water.
- Storage Technology: Cement-lined reservoirs (puteoli) reduced evaporation and waste

As other indirect estimation, this method has some limitations which are:

- Data Gaps: No direct records of soldiers' daily water use survive.
- Regional Disparities: Consumption in Italy differed vastly from besieged outposts like Masada.
- Population Estimates: Demographic figures for Roman cities remain debated

In conclusion, synthesizing historical and archaeological data, the daily water consumption of Roman soldiers in Italy two millennia ago is estimated at **7–18 liters per person**. This range fluctuated based on circumstances, dipping to **5 liters** during scarcity or rising to **50 liters** in aqueduct-served cities. Such estimates not only illuminate daily life in the Roman military but also underscore the empire's logistical prowess in water management.

4.2.3.2. Water demand in the modern age: standard consumption

For the purposes of calculating the annual water requirement,

Starting from data reported in chapter 3 on Forte Torre Building (Table 11 and Table 12), the annual water requirement of the building was evaluated from a the daily users water consumption.

First, the presence on an annual basis was assessed for each user type In particular, a presence of only 6 months out of 12 was considered for the "Tourist" users and a constant presence of 12 months per year for the "domestic" and "office" users, who reside or work permanently in the respective environments.
Then the daily presence was estimated using the calculation of the Full Time Equivalent Occupants (Full Time Equivalent – FTE). The number of Full Time Equivalent Occupants was calculated on the basis of a standard of 8 hours per day of presence period (40 hours per week). An 8-hour presence has an FTE value equal to 1.0 while a part-time presence has an FTE value based on the hours of presence per day divided by 8. For the working users ("office"), the presence was esteemed considering a working day of 8 h. The number of temporary presences (tourists) was also estimated as FTE, considering as a first hypothesis an average stay of 1 h in the Museum. The number of current residents was provided by the Municipality.
Table 15 shows the calculation of the daily number of actual users, distinguished by type of user and activity, the number of Full-Time Equivalent Occupants (FTE) and the number of days of annual presence. (source: ENEA)

Table 15. Estimation Water consumption per person

Building	Activity	User Type	Daily Users (users/day)	FTE	Daily FTE (FTE/day)	Annual User Presence (days/year/user)
Forte Torre	Archaeological Museum	Tourist	7	0.125	0.87	183
	Archaeological Museum	Office	1	1	1	235 (2 weekly rest days + 26 vacation days)
	Social Assistance Offices	Office	1	0.9	0.9	235 (2 weekly rest days + 26 vacation days)
	Marine Reserve Offices	Office	3	0.9	2.7	235 (2 weekly rest days + 26 vacation days)
	Municipal Offices (Permanent & Temporary Employees)	Office	7	0.9	6.3	235 (2 weekly rest days + 26 vacation days)
	Council Chamber (Politicians)	Office	1	1	1	235 (2 weekly rest days + 26 vacation days)
	Apartments	Residential	5	1	5	365

Then the standard consumption of each" user was evaluated. Where present, data obtained from on-site inspections were used, integrated with literature data. Below is a table showing the details of water consumption by type of user (Table 16).

It should be noted that the consumption obtained for the "office" user is comparable to that reported in the "2015 NON-RESIDENTIAL ITACA National PROTOCOL", for commercial/industrial users, equal to 50 L per person per day.

As regards the "domestic" user, it is comparable to the estimates conducted by ENEA on the daily per capita consumption, between 175 - 235 L/ab/day, reported in Table 17, staring from resident and floating population, as well as with data reported in chapter 3 starting from the top-down estimation (cf. 3.5.1). Furthermore, the values determined for the "domestic" user are in line with the values reported in the literature in terms of percentage of use

Table 16. Standard Usage of Hydrosanitary Equipment (source: ENEA)

User	Consumption Detail	Standard Type	Daily Uses	Daily Uses min/user/days	Standard Consumption (L/user/day)
Office Usage	**Office Usage**				
	Toilet (WC)	10.0 Lpf	3.0 [a]		30.0 L/user/day
	Washbasin Tap	9.0 Lpm [b]	3.0 [a]	1.0 min *	9.0 L/user/day
	Cleaning	-	-		7.5 + L/user/day
	Total				**46.5 L/user/day**
Tourist Usage	**Tourist Usage**				
	Toilet (WC)	10.0 Lpf	1.0 [a]		10.0 L/user/day
	Washbasin Tap	9.0 Lpm	2.0 [a]	0.6 min *	5.4 L/user/day
	Cleaning	-	-		7.5 + L/user/day
	Total				**22.9 L/user/day**
Domestic Usage.5	**Domestic Usage**				
	Toilet (WC)	10.0 Lpf	5.0 [a]		50.0 L/user/day
	Washbasin Tap	9.0 Lpm	5.0 [a]	5.0 min **	45.0 L/user/day
	Bidet Tap	9.0 Lpm	1.0 [a]	1.0 min **	9.0 L/user/day
	Shower	9.0 Lpm	1.0 [a]	5.0 min ***	45.0 L/user/day
	Kitchen Sink	9.0 Lpm	4.0 [a]	4.0 min **	36.0 L/user/day
	Cleaning	-	-		7.5 + L/user/day
	Other Uses (Laundry, etc.)	-	-		40.0 L/user/day
	Total				**232.5 L/user/day**[a1]

Legend:
- Lpf = Liters per flush
- Lpm = Liters per minute
- * 20 seconds for handwashing
- ** 60 seconds for kitchen and bidet taps
- *** 300 seconds for showers
- + Residential sector consumption, equal to 5% of the average domestic per capita consumption (150 L/person/day).

References:

[a] GBC Historic Building® Manual for the restoration and sustainable redevelopment of historic buildings (2016 edition, revised May 2017).

[b] On-site survey data.

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Table 17. Estimation of Residential Water Demand

Parameter	Unit of Measurement	Period (June - September)	Period (October - May)
Resident Population	Inhabitants (Ab)	700	300
Floating Population	Inhabitants (Ab)	2000	50
Per Capita Consumption (Residents)	L/d/Ab	250	250
Per Capita Consumption (Floating Population)	L/d/Ab	150	150
Daily Demand	m³/d	475	82.5
Monthly Demand	m³/month	14,250	2,475
Total Demand (June - September)	m³/period (L/Ab/d)	57,000 (175)	-
Total Demand (October - May)	m³/period (L/Ab/d)	-	19,800 (235)
Annual Demand	m³/year	76,800	

From the estimate made, it is possible to state that Forte Torre consumes approximately 558 cubic meters of water per year (Table 18). The analysis of the data also shows that approximately 76% of water consumption comes from apartments, while the remaining 24% comes from the use of toilets by office and tourist users. The use of the toilet accounts for 64% in the case of office users, 50% in the case of tourist users and 20% in the case of domestic users. The volume of water used therefore for purposes related to the toilet alone is approximately 83m3/year for office users, approximately 1.8m3/year for tourist users and 41m3/year for domestic users, for a total of 84.8m3/year.

Table 18. Forte Torre standard consumption in modern era**Activity**	**User Type**	**Daily FTE (FTE/day)**	**Annual Presence per User (days/year/user)**	**Per Capita Consumption (L/user/day)**	**Annual Consumption (m³/year)**
Archaeological Museum	Tourist	0.87	183	22.9	3.6
Archaeological Museum	Office	1	235	46.5	10.9
Social Assistance Offices	Office	0.9	235	46.5	9.8
Marine Reserve Offices	Office	2.7	235	46.5	29.5
Municipal Offices (Permanent and Temporary Employees)	Office	6.3	235	46.5	68.8
Council Hall (Politicians)	Office	1	235	46.5	10.9
Apartments	Residential	5	365	232.5	424.3
Total	-	-	-	-	**557.8**

4.2.3.3. Water demand in the modern age: efficient consumption

In this thesis an efficient consumption of water in Forte Torre Building has been considered in order to perform simulation in moder era. Some possible water saving measures have been considered.
In particular, the water saving actions that can be implemented are:
a) the installation of dual-button WC for all identified users. In particular, the installation of a dual-flow system has been planned (3 LPF reduced jet, 6 LPF full jet).
b) the installation of high-efficiency water taps for bathroom sinks, equipped where possible with photocells, for “office”, “study”, “workers”, “tourist” users, guaranteeing a flow of 1.9 liters per minute in the case of classic taps or 1 liter per cycle in the case of timed taps;
c) the installation of high water efficiency taps for bathroom showers, guaranteeing a flow of 6 litres per minute.

Table 19. Efficient Usage of Hydrosanitary Equipment (source: ENEA)

User	Consumption Detail	Standard Type	Daily Uses	Daily Uses min/user/days	Standard Consumption (L/user/day)
Office Usage	**Office Usage**				
	Toilet (WC)	4.0 Lpf 6.0 Lpf	3.0 [a] 1.0 [a]		14.0 L/user/day
	Washbasin Tap	1.9 Lpm [a]	3.0 [a]	1.0 min *	1.9 L/user/day
	Cleaning	-	-		7.5 + L/user/day
	Total				**23.4 L/user/day**
Tourist Usage	**Tourist Usage**				
	Toilet (WC)	4.0 Lpf 6.0 Lpf	1.0 [a]		4.0 L/user/day
	Washbasin Tap	1.9 Lpm	2.0 [a]	0.6 min *	1.25 L/user/day
	Cleaning	-	-		7.5 + L/user/day
	Total				**12.75 L/user/day**
Domestic Usage.5	**Domestic Usage**				
	Toilet (WC)	4.0 Lpf 6.0 Lpf	4.0 [a] 1.0 [a]		22.0 L/user/day
	Washbasin Tap	1.9 Lpm [b]	5.0 [a]	5.0 min **	9.5 L/user/day
	Bidet Tap	1.9 Lpm [b]	1.0 [a]	1.0 min **	1.9 L/user/day
	Shower	6.0 Lpm [b]	1.0 [a]	5.0 min ***	30 L/user/day
	Kitchen Sink	1.9 Lpm [b]	4.0 [a]	4.0 min **	7.6 L/user/day
	Cleaning	-	-		7.5 + L/user/day
	Other Uses (Laundry, etc.)	-	-		20.0 L/user/day
	Total				**98.5 L/user/day**[a1]

Legend:
- Lpf = Liters per flush
- Lpm = Liters per minute
- * 20 seconds for handwashing
- ** 60 seconds for kitchen and bidet taps
- *** 300 seconds for showers
- + Residential sector consumption, equal to 5% of the average domestic per capita consumption (150 L/person/day).

References:

[a] GBC Historic Building® Manual for the restoration and sustainable redevelopment of historic buildings (2016 edition, revised May 2017).

[b] On-site survey data.

This assumption allow to consider an efficient water consumption of almost 100 L/ab/d that can be used in the following simulations.

4.2.4. Long-term rainfall (water supply)

An overview of rainfall patterns during last years was provided in chapter 3. In this part, the most effective climate data useful for simulation of rainwater potential recovery is mentioned. Table 20 presents the number of days that have more than 20mm rain fall while Table 21 and Fig. 34 provide average precipitation in depth (mm per year) in two periods

Table 20. The number of days that have more than 20mm rain fall

Year	Count of > 20 mm	Max of > 20 mm (mm)
2019	11	49
2020	6	59.9
2021	11	68
2022	7	150.8
2023	7	39
2024	2	36.3
Grand Total	**44**	**150.8**

Table 21. Trend of rainfall

Period	Average Precipitation (1991-2020) (mm)	Average Precipitation (1991-2024) (mm)
January	80	52
February	70	27
March	40	25
April	40	27
May	15	24
June	15	16
July	5	4
August	10	11
September	65	46
October	100	38
November	120	86
December	100	52
Total	**660**	**407**

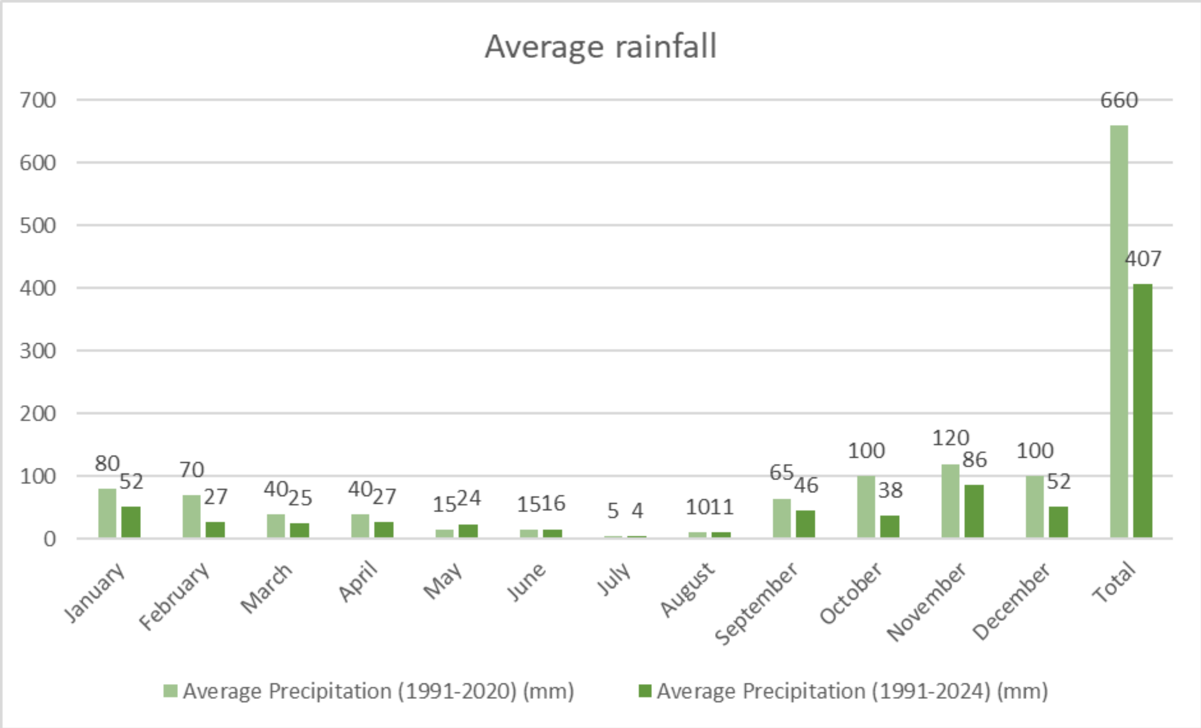


Fig 34. Graph of average rainfall

4.3. Case Study: Forte Torre

4.3.1. Data analysis

In the initial phase, data for the water collection area—designated as SC1, a municipal building—was input into the system. Rain gauge and time series configurations were established to monitor precipitation patterns and integrate external datasets. Key dates and rainfall intensities were added from company reports, forming the basis for subsequent analysis.

- SC1 Building Specifications

The dimensions and imperviousness of the building were derived from official AutoCAD maps provided by the municipality (Fig. 35, 36). These parameters are summarized in the Table 22.

Table 22. Features of SC1 (forte tore)

Property	Value
Area	0.6 m^2
Width	20 m
Imprv	100%

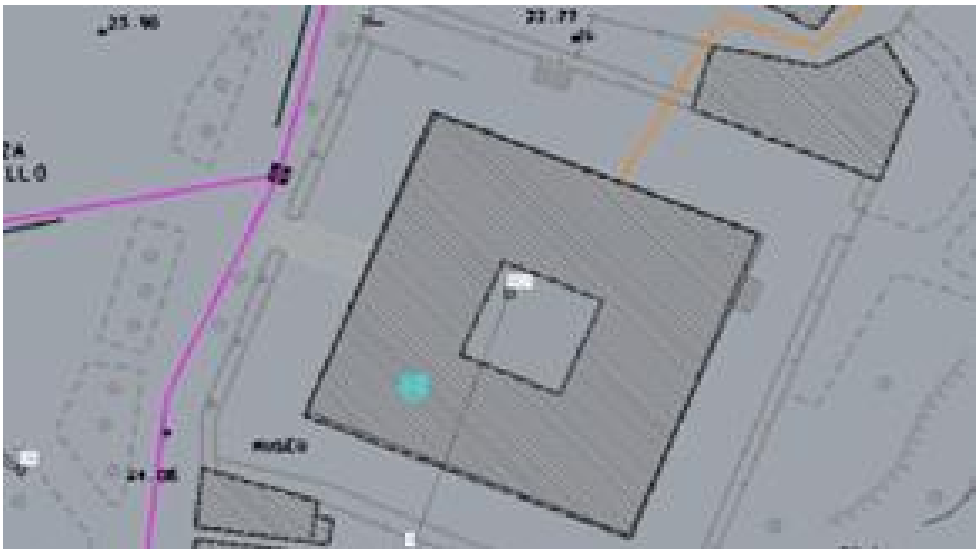
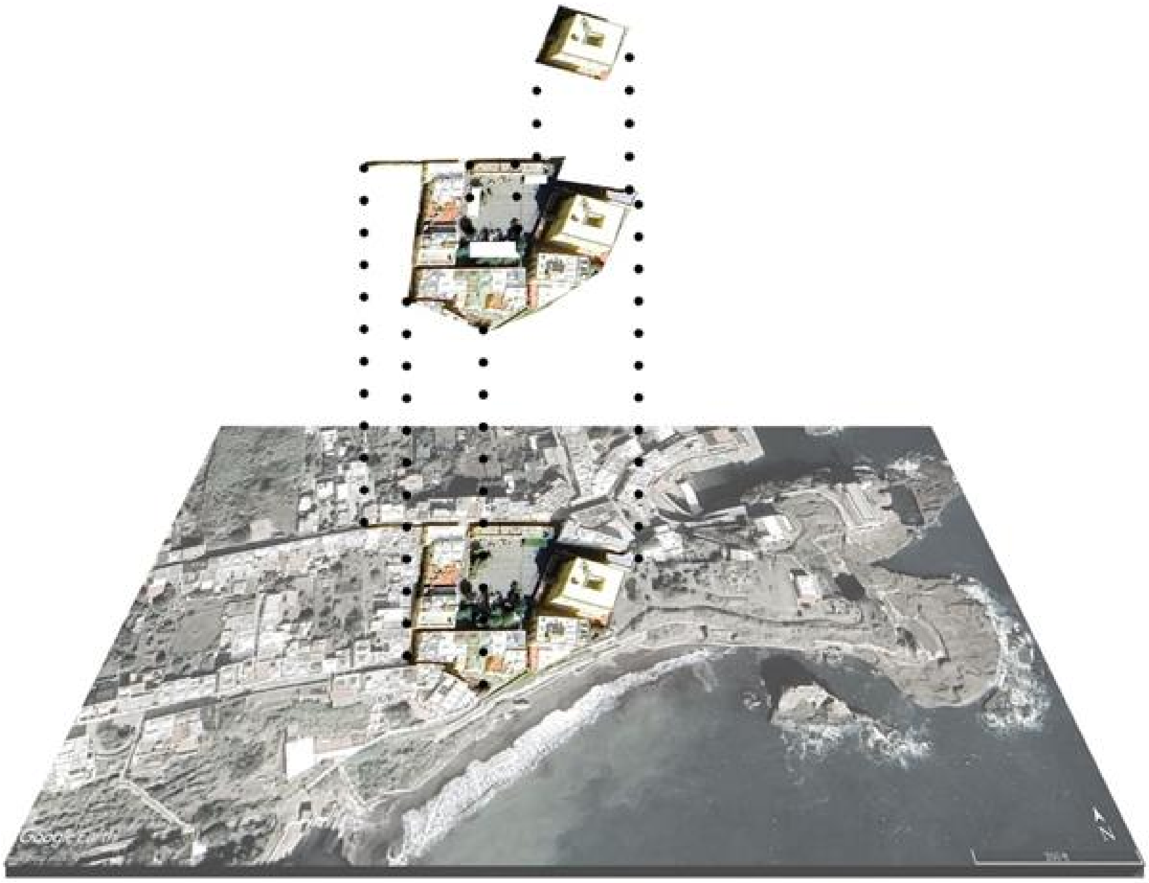
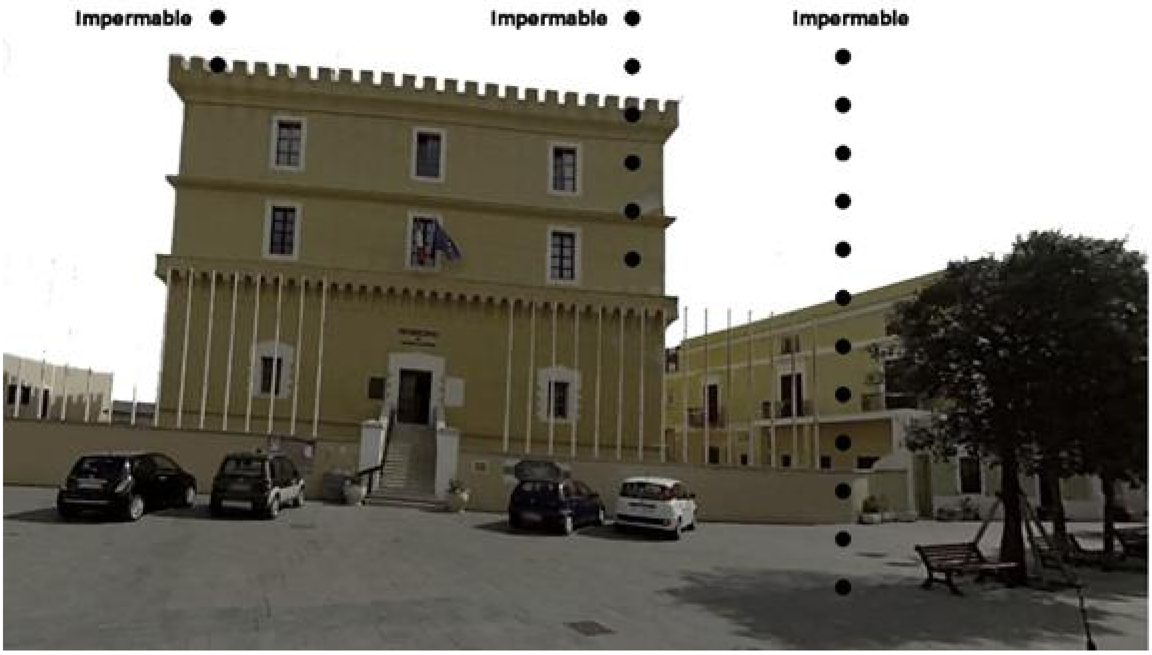


Figure 35. Forte Torre catchment area

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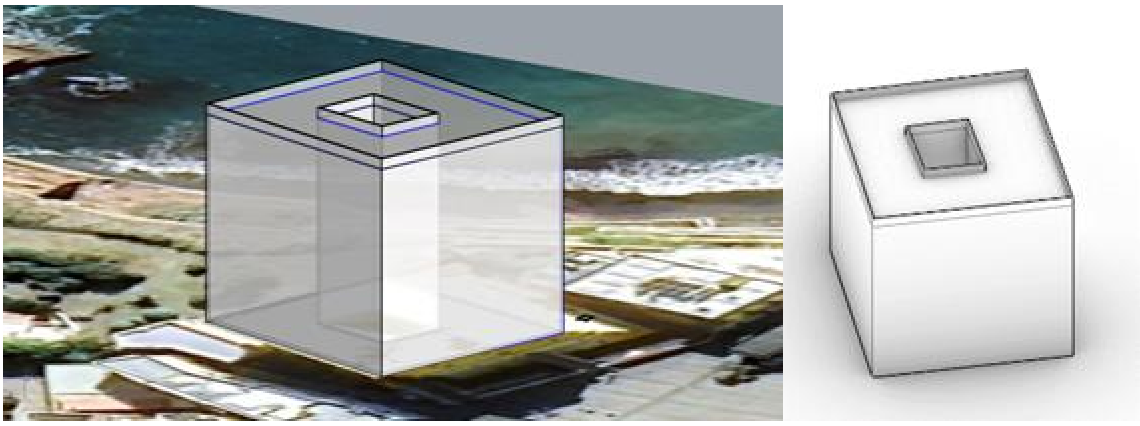


Fig 36. Building and site situation (SWMM simulation)

Based on field measurements, also the water storage was defined in the software. A weir connected to the outlet was implemented to regulate the water volume. The reservoir's key dimensions are reported in Table 23 and Fig. 37.

Table 24. features of water storage that imported in SWMM

water storage	Value (m)
Length	4.64
Width	6.64

The design accounts for a target water volume of approximately 140 m³, considering the weir's effect on the outlet flow.

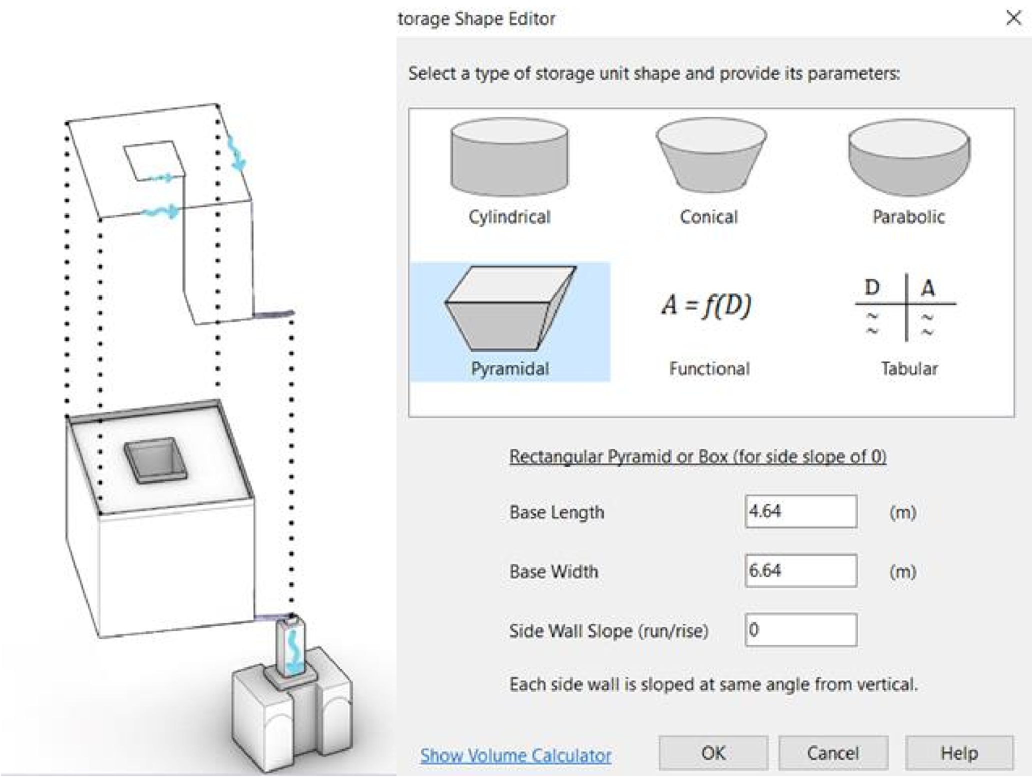


Fig 37. Water harvesting and water collection in building and storage volume (SWMM simulation)

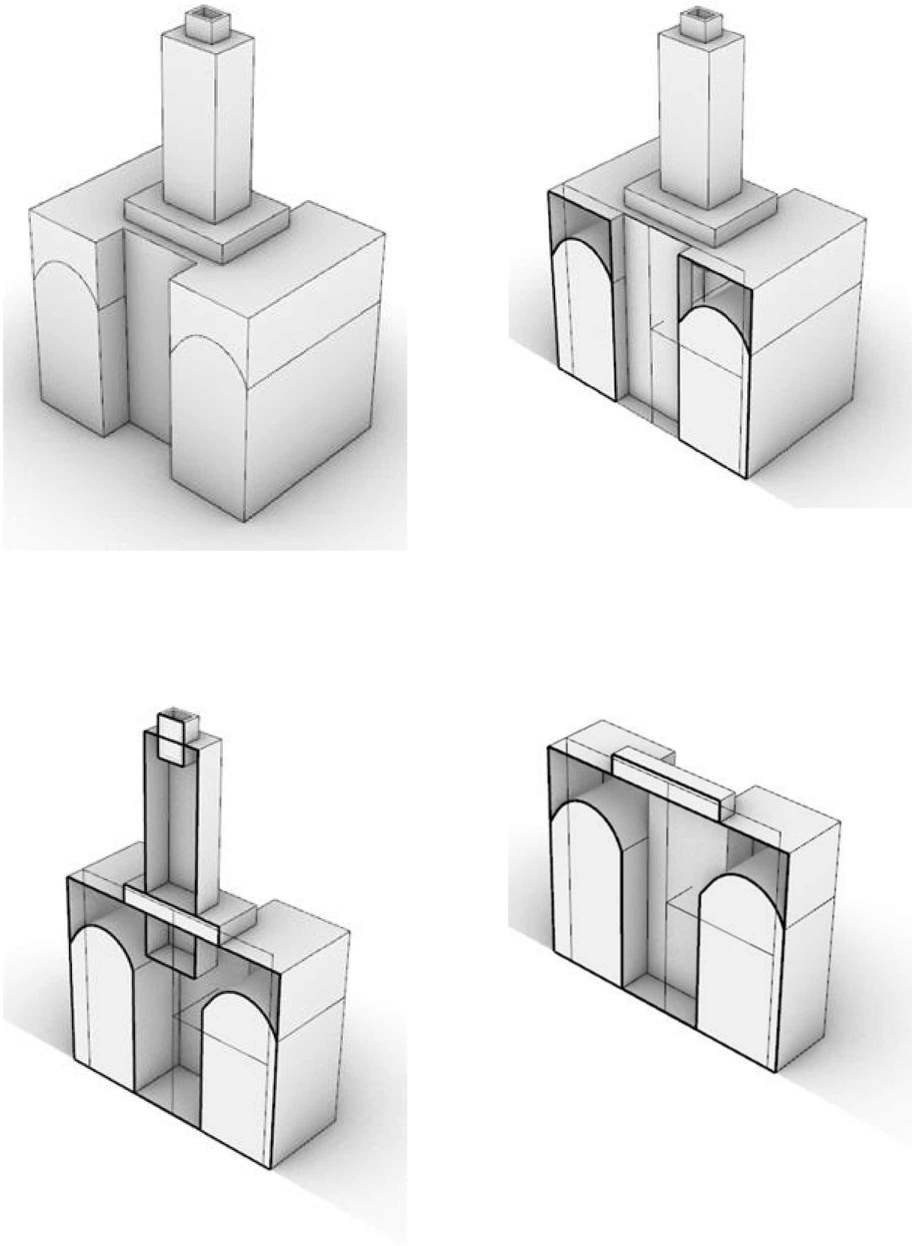


Fig 38. Tank filling trend chart without considering water usage (source author)

4.3.2. Simulation

The simulation performed in this thesis for the case study encompasses three distinct scenarios:

1. The first scenario evaluates the process of storage filling, excluding any consumption.

2. The second scenario estimates water consumption indirectly, focusing on the habits of ancient populations.

3. The third scenario provides an estimation based on ENEA's model, tailored for the modern era.

4.3.2.1. Scenario 1: Process of storage filling

Through this partial simulation, from January 2019, a minimum of 150 days of rainwater harvesting is required to fill up the storage fully. The filling is presented in Table 25 and Figures 39 and 40., only 150 days of rainwater harvesting is sufficient to fill this storage. Details of the filling process are reported in Table 25 and Fig’s 39 and 40.

Table 25. Summary of analyzing filling graph

Time Range (Days)	Approx. Volume (m^3)	Analysis
0 – 5	0 – 10	The reservoir is initially almost empty with minimal inflow.
5 – 15	10 – 30	Gradual increase in water volume indicates moderate inflow.
15 – 20	30 – 60	Noticeable jump in volume suggests a heavier or more continuous inflow.
20 – 30	60 – 90	Sharp increase continues, reservoir is filling rapidly.
50 – 100	90 – 95	The reservoir reaches near capacity and stabilizes with minimal change.

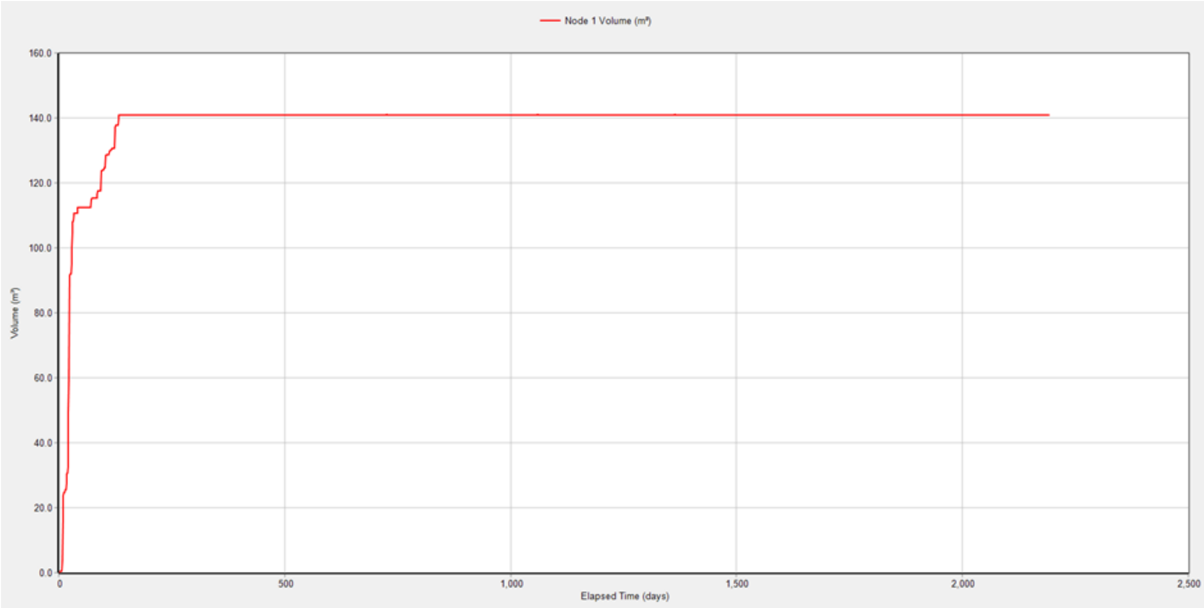


Fig 39. Tank filling trend chart without considering water usage

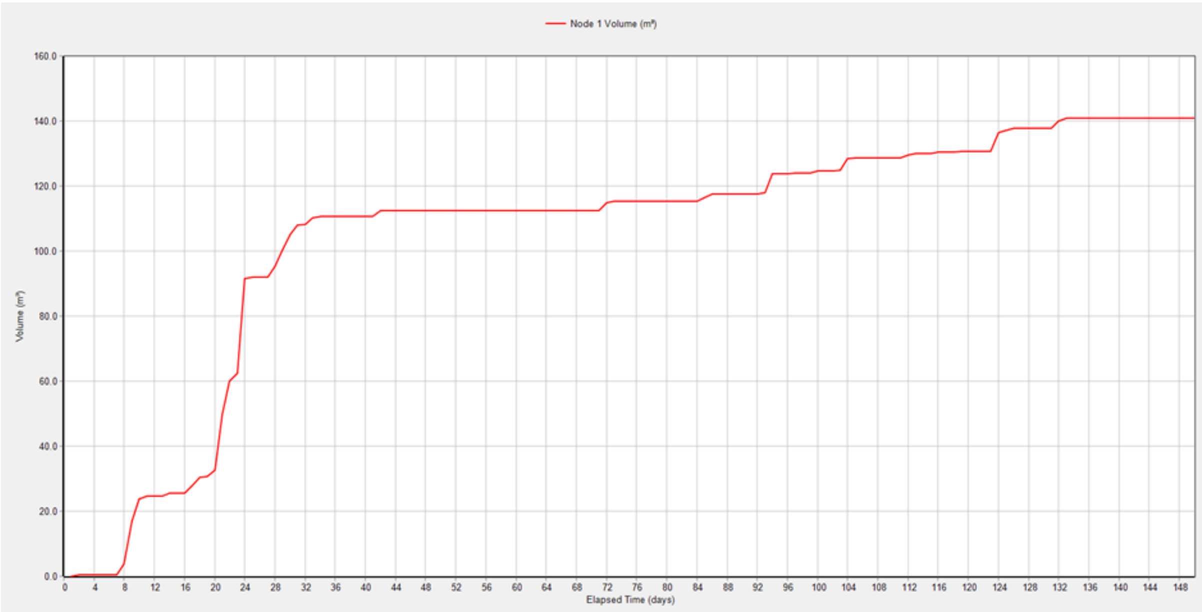


Fig 40. Tank filling trend chart without considering water usage in first 150 days

4.3.2.2. Ancient populations

In this part of simulation we consider some assumption for water consuming based of data collection that are mentioned in previous parts, and summarized in Table 26.

Table 26. Summary of assumption for consumption in the scenario

Number of users	20
Water demand for each person	15 L

The data spans a period from Day 1 to Day 2191 (the recorded file of rainfall), covering approximately six years (Fig. 40, 41). The recorded water volume in the storage begins at 0 m³, reaches a peak of 141.9 m³ on Day 280, and eventually declines to 61.13 m³ by the end of the dataset.

The trends observed in the data can be divided into three phases. Initially, during Days 1 to 30, the water volume increases steadily from 0 m³ to 96.41 m³, suggesting gradual filling of the tank together with minimal water consumption during this period. In the mid-term phase, spanning Days 30 to 1350, significant fluctuations are evident, with peaks reaching up to 141.88 m³ on Day 451. These variations could be attributed to seasonal water demand, irregular refilling schedules, or environmental factors such as rainfall and evaporation. Finally, in the long-term phase, from Day 1350 to Day 2191, the water volume exhibits a consistent decline, dropping to 61.13 m³. This decline may result from decreased precipitation.

Key observations from the dataset highlight notable peaks and low points (Table 27). The highest recorded volumes occur on Days 280 (141.9 m³), 451 (141.88 m³), and 516 (141.83 m³). Conversely, the lowest volumes are observed on Day 1 (0 m³, indicating an empty water storage) and Day 2191 (61.13 m³, marking the lowest volume at the end of the dataset).

The fluctuations in water volume are likely influenced by several factors. Non-uniform refilling schedules might contribute to variability. Notably, recurring volume peaks around 140 m³ approximately every 300 days—such as on Days 280, 650, and 1000—suggest the presence of seasonal cycles.

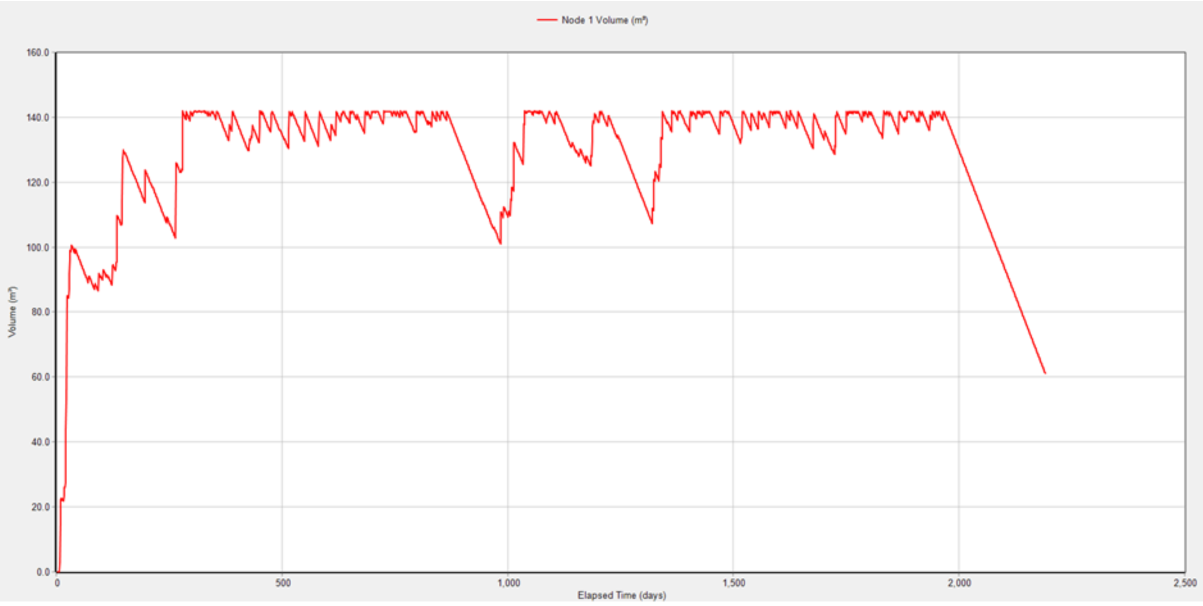


Fig 41. Graph of water volume in the storage during the whole period.

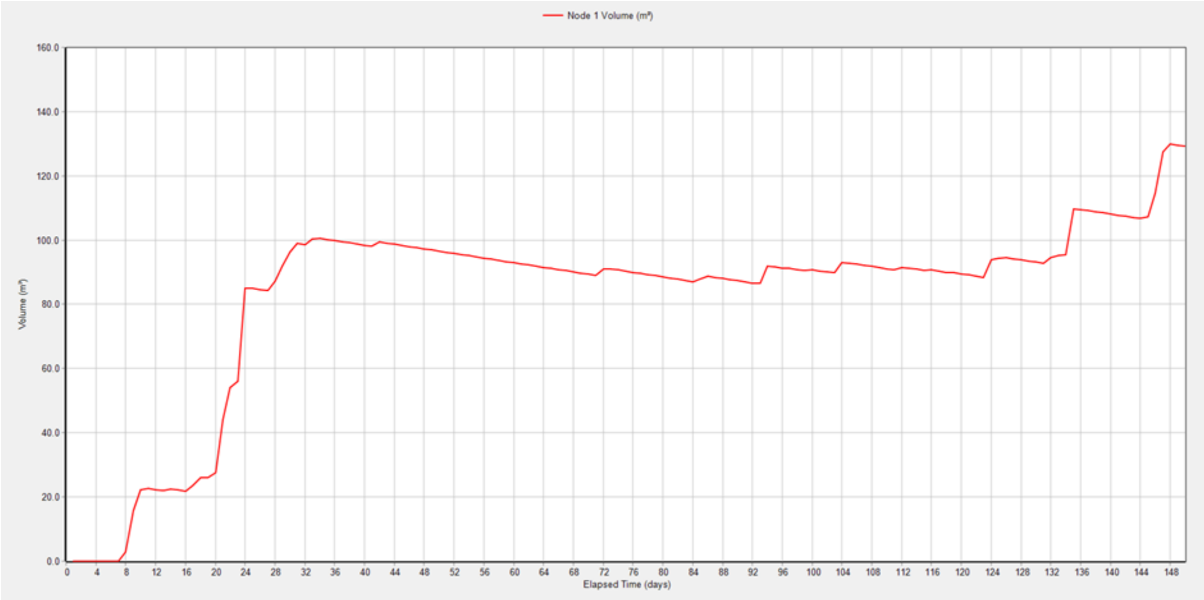


Fig 42. Graph of water volume in the storage during the 150 of first days.

Table 27. The count of days for Ancient populations simulation

Storage Status	Number of Days
Empty Tank (0 m³)	6 day
Peak Days (≥140 m³)	72 days

In the Ancient Population Scenario, the water consumption was calculated at 15 liters per person per day, accommodating 20 users. This modest demand, combined with consistent rainfall patterns, resulted in the water tank rarely being completely emptied. Only six days of tank depletion was recorded throughout the scenario, highlighting the system's resilience under ancient usage conditions.

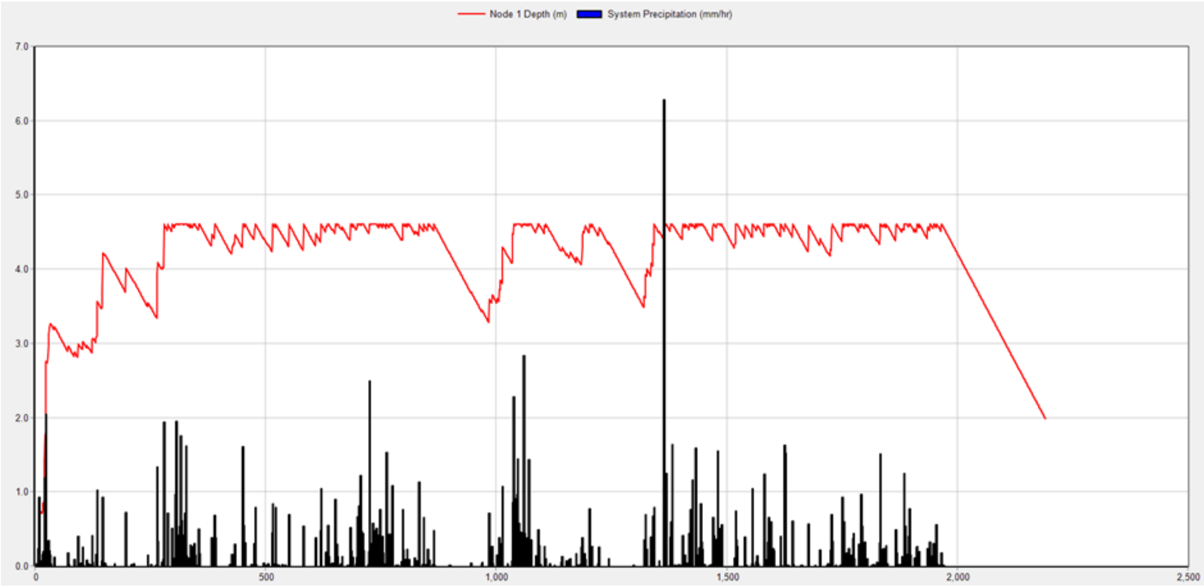


Fig 43. Water tank depth chart and its overlap with rainfall.

Fig. 43 shows rhe daily water depth measurements (in meters) collected from a storage tank over a period of 2,191 days. This allowedto identify instances where the water level dropped below 1 meter—a critical threshold that may signal potential operational or supply concerns.
From Fig. 43 it can be observed that for the first 20 consecutive days (Days 1–20), the water depth remained below 1 meter. The lowest recorded depth was 0 meters (Days 1–7), followed by a gradual rise to 0.89 meters by Day 20. From Day 21 onward, the water level consistently stayed above 1 meter, exhibiting occasional fluctuations but without sustained declines below this threshold. A continuous 20-day period of low water levels might indicate initial filling delays, calibration discrepancies, or early operational adjustments. Understanding these trends can provide valuable insights for optimizing storage and supply management.

4.3.2.3. Assessment of Tank Water Availability and Daily User Capacity

To evaluate the sustainable use of the rainwater tank and determine its capacity to serve a consistent number of users without falling below a critical volume, a spreadsheet-based simulation was conducted. The analysis aimed to identify the maximum number of individuals who can draw water from the tank daily, under the condition that the tank volume must never drop below a safe operational threshold.

Given the practical considerations related to maintenance, sedimentation, and structural safety, one meter of the tank's depth was reserved as a buffer zone. This unused volume accounts for the accumulation of sediment and ensures that intake or drainage mechanisms are not compromised during operation. Based on the geometry of the tank, this buffer translates into a fixed minimum operational volume of 24,000 liters, which was used as the critical lower limit in the simulation.

The data used in this analysis were extracted from a SWMM model output that simulated daily tank volumes under realistic rainfall conditions and local catchment characteristics. The SWMM output was exported in Excel format, allowing further post-processing and operational analysis. A fixed daily consumption rate of 15 liters per person was applied to this dataset. The simulation assumed a constant number of users each day (e.g., 30 people), and for each date, the remaining tank volume after consumption was calculated.

A column titled Adjusted_Volume was created, in which a conditional formula ensured that daily consumption would only be deducted if the resulting volume remained above the 24,000-liter threshold. This condition was expressed in Excel as:

```
=IF(Previous_Day_Adjusted_Volume - Daily_Consumption >= 24000,
Previous_Day_Adjusted_Volume - Daily_Consumption, Previous_Day_Adjusted_Volume)
```

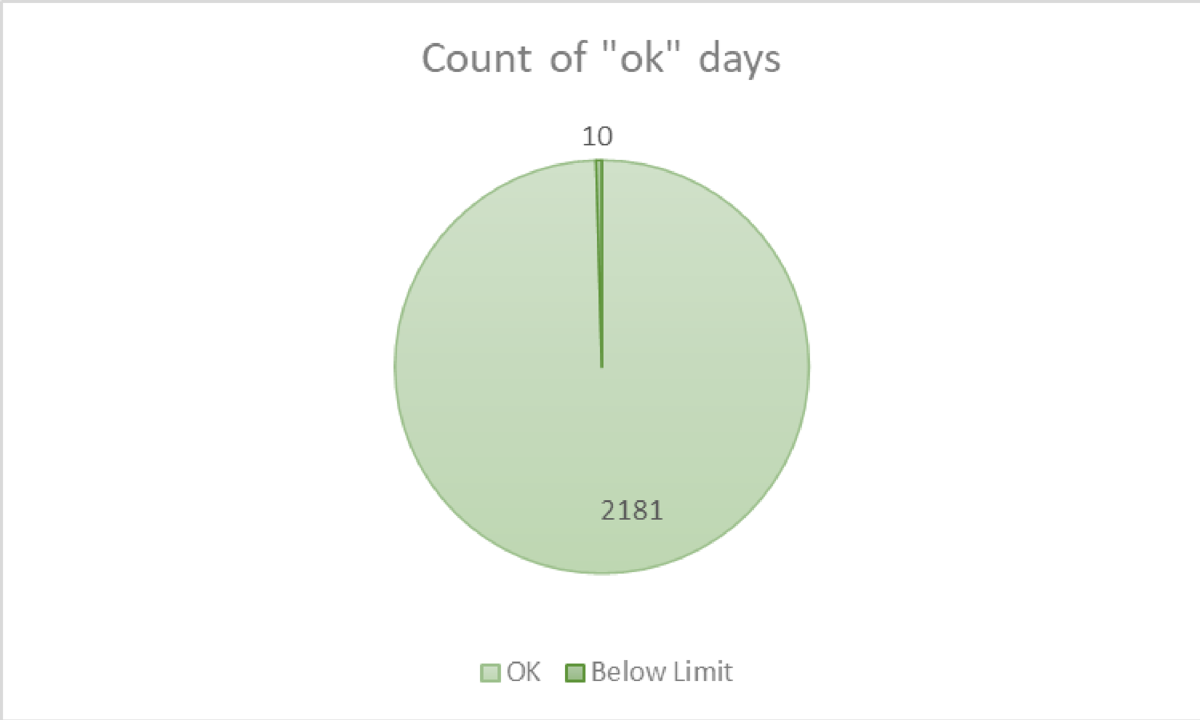
Subsequently, a Status column was introduced to classify each day as either "OK" (tank volume ≥ 24,000 L) or "Below Limit" (tank volume < 24,000 L). This was achieved using the following formula:

```
=IF(Adjusted_Volume < 24000, "Below Limit", "OK")
```

By applying the COUNTIF function, the number of days in each status category was determined:

```
=COUNTIF(Status_Column, "OK")
=COUNTIF(Status_Column, "Below Limit")
```

These counts were then used to assess the long-term reliability of the tank system in supporting non-potable water demand. Additionally, the results were visualized using a pie chart or bar chart, illustrating the proportion of operational days versus days of water shortage. This approach provided a clear and intuitive representation of system resilience, supporting decision-making for setting realistic user limits and designing supplementary storage or demand management strategies.



According to the results, assuming that the tank was filled after the first 10 days of the simulation and a daily fixed population of 30 users, the system was able to provide a stable water supply without the volume dropping below the safety threshold at any point in time. This confirms the tank's suitability for non-potable reuse under moderate consumption levels and validates its role as a resilient component of small-island water infrastructure.

4.3.2.4. Modern era

In this part of simulation we consider some assumption for water consuming based of data collection that are mentioned in previous parts, and summarized in Table 28.

Table 28. Summary of assumption for consumption in the scenario

Number of users	15
Water demand for each person	100 L

The data provides insights into the water volume dynamics within the storage over a monitoring period of 2,191 days, roughly spanning six years (Fig. 44, 45).

Key trends in the dataset can be grouped into three distinct phases. The first phase, covering Days 1 to 20, represents the initial filling period. During the first week (Days 1–7), the volume remains near 0 m³, suggesting that the storage system was either empty or inactive. From Days 8 to 20, a gradual increase in volume is observed, reaching 27.5 m³, likely due to controlled inflow or the start of the filling process.

The second phase, spanning Days 21 to 135, is characterized by rapid growth and subsequent stabilization. Between Days 21 and 36, the volume sharply increases from 27.5 m³ to 100.56 m³, a spike that could be attributed to seasonal rainfall. Following this rapid increase, the volume stabilizes within the range of 90–100 m³ from Days 37 to 135, exhibiting only minor fluctuations. This phase suggests a balance between water inflow and outflow, reflecting normal operating conditions.

The third phase, occurring over the remaining period from Day 136 to Day 2,191, reveals a long-term decline in water volume. This gradual reduction from approximately 100 m³ to 61 m³ could be indicative of persistent drought conditions, reduced water inflow, , or system inefficiencies such as evaporation . Despite this declining trend, the data also reveals short-term fluctuations, including notable spikes. For instance, a peak of 140 m³ is recorded on Day 280, possibly due to replenishment events.

Critical observations highlight both sudden inflow events and abrupt declines. Significant inflows include a 60% volume increase on Day 21 (from 27.5 m³ to 44.16 m³) and the peak volume of 140m³ on Day 280. Another unexpected spike to 140 m³ occurs on Day 1,707 after a period of prolonged low volumes. Abrupt declines are observed on Day 197, where the volume drops from 123.7 m³ to 110.8 m³, and over a 150-day period starting on Day 2,043, where the volume sharply decreases from 140 m³ to 61.13 m³.

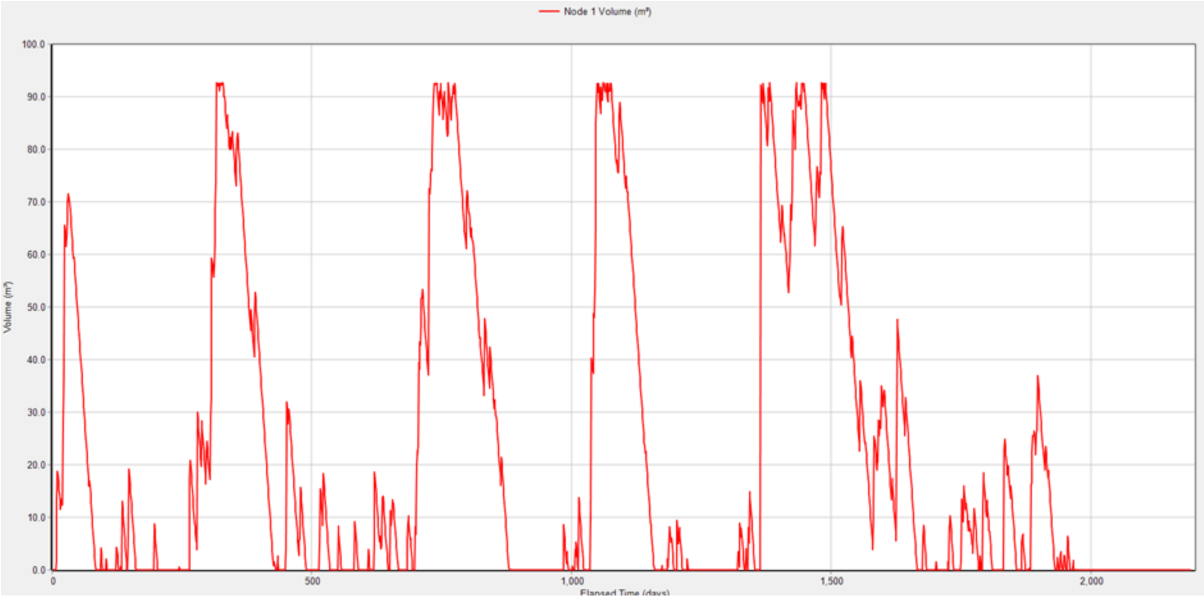


Fig 44. Graph of water volume in the storage in modern era during the whole period.

Fig 45. Graph of water volume in the storage during the 150 of first days

Table 29. The count of days for modern populations simulation

Storage Status	Number of Days
Empty (0 m³)	1094 day
Full (≥140 m³)	126 day
Intermediate	2,165 day

In the Modern Era Scenario, water consumption was estimated at 100 liters per person per day, serving a total of 15 users. This elevated demand, paired with a significant decrease in rainfall resulted in the tank being empty for about 100 days. This scenario highlights the challenges posed by higher usage rates and reduced precipitation in maintaining water storage stability.

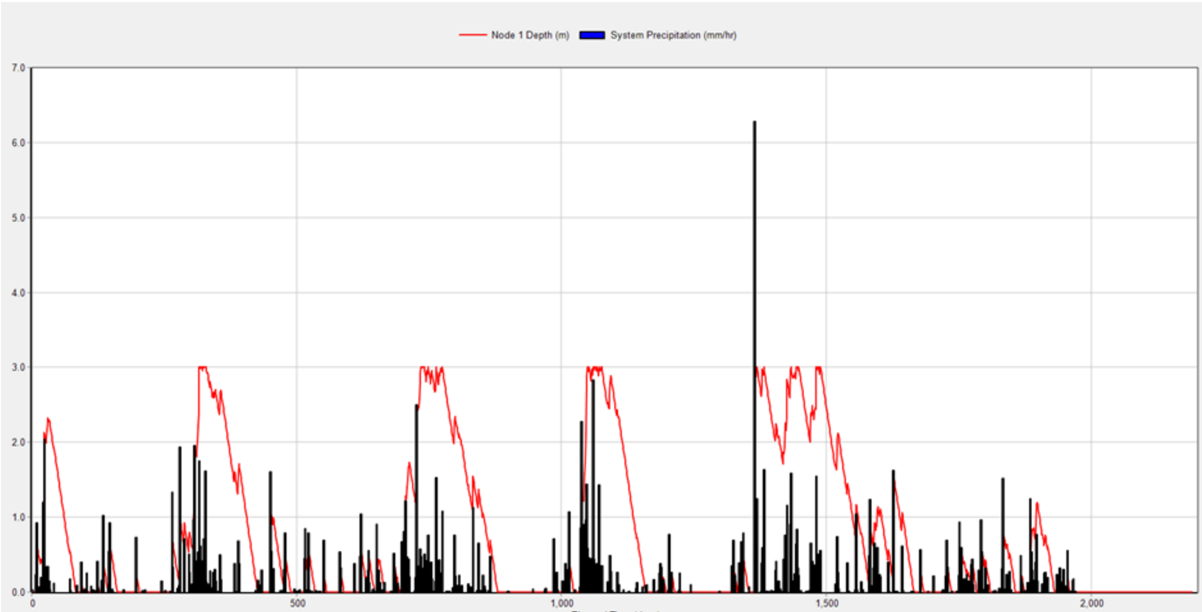


Fig 46. Graph of water Depth and rainfall in the storage during the 150 of first days

According to the simulation for the modern era, and based on the seasonal non-potable water demand profile developed in the previous section, the tank proved to be capable of meeting daily needs without the stored volume ever dropping below the critical safety threshold of 24,000 liters. This analysis assumed that the tank reached full capacity after the initial 10 days of the simulation period and considered the combined demand for toilet use, fire safety, irrigation, and agricultural needs. Under these realistic operating conditions, the system demonstrated a stable performance throughout the year, confirming its suitability for non-potable reuse in modern scenarios.

Given the calculated average daily consumption, the storage is able to provide a reliable and uninterrupted supply of non-potable water for up to five people per day, while maintaining the required safety buffer.

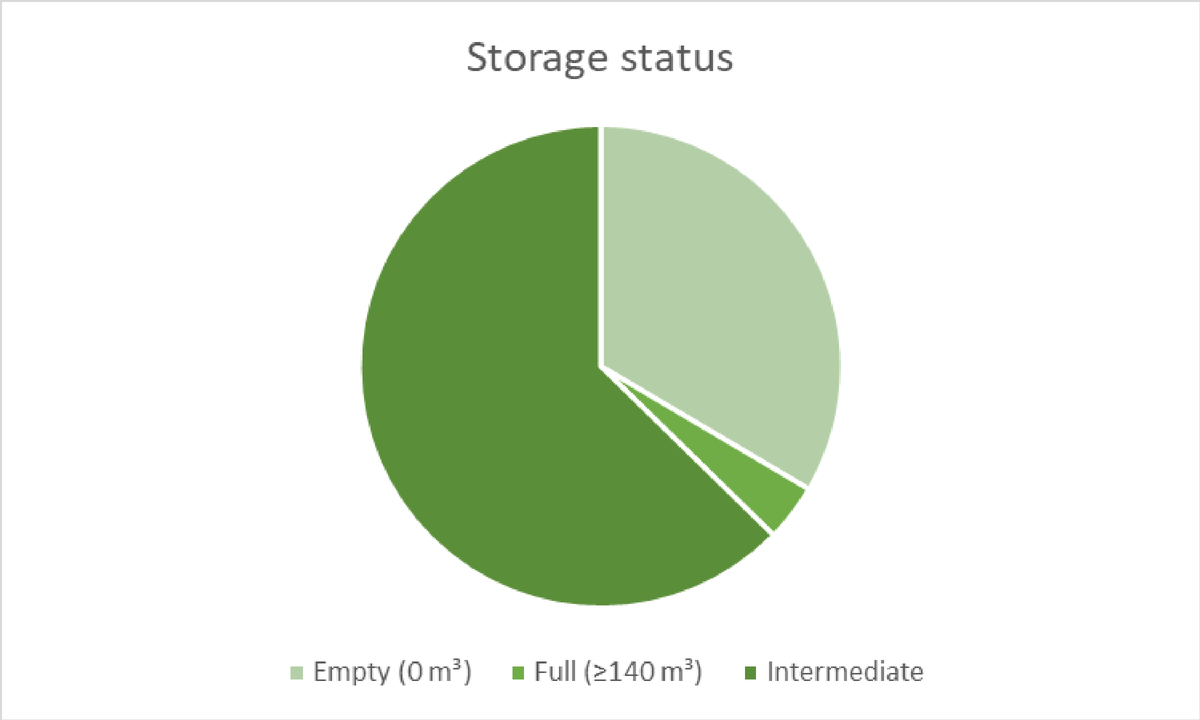


Fig 47. Portion of water storage status during the period

5. Conclusion

This thesis explored the potential for integrating ancient water infrastructures in contemporary sustainable water management systems, and it was specifically focused on the case study of the island of Ventotene. The research was based on small island vulnerabilities, where water scarcity, climatic variability, and environmental degradation pose significant threats to long-term sustainability. By examining Ventotene's ancient water reservoirs—Roman and, in particular, Bourbonic-era ones—and their feasibility for reuse as modern rainwater harvesting systems, the study provided a multidisciplinary evaluation linking heritage preservation, engineering analysis, and climatically responsive planning.

The study demonstrates that, despite their age and varying states of decay, the ancient cisterns possess preferable structural and spatial characteristics that make them suitable for adaptive reuse. By utilizing remote sensing, GIS spatial analysis, and hydraulic simulation using SWMM software, the research demonstrated that these systems can be effectively restored to supply non-potable water needs, such as irrigation, toilet flushing, and the watering of urban green areas. The past and present simulation scenarios confirmed that with moderate demand and good maintenance, the chosen tanks are able to supply water stably throughout the year.

One of the major findings of this study is that the synergy between ancient knowledge and modern technologies has the potential to provide low-impact, replicable water management solutions in similar Mediterranean and small-island environments. Through the inclusion of a real case study and the quantification of rainwater harvesting potential, the research not only validated the reuse of ancient tanks as technically viable, but also discusses their environmental, economic, and cultural benefits.

Furthermore, the proposed modeling approach and Excel-based seasonal consumption simulation provide a replicable means of determining the performance of rainwater harvesting systems in the presence of seasonal variation and infrastructure limitation. The study also emphasized leaving a safety margin in the storage tanks (i.e., 1 meter from the bottom) to facilitate sedimentation, maintenance, and emergency storage, thereby ensuring operation sustainability.

Based on the simulations conducted in this study, it was observed that if water consumption is carefully regulated, the available water resources historically sustained a population of around 30 people. However, in modern times, due to increased individual water demand and changing consumption patterns, the same resource can provide a stable water supply for only 5 individuals. This finding underscores the significance of adapting ancient water infrastructure to contemporary usage while considering population growth, urbanization, and technological advancements.

Briefly, Ventotene is a microcosm of how islands—and areas rich in heritage—can lead the way in sustainable innovation drawing on the past to meet the challenges of the future. The study contributes to a growing body of research fostering cross-disciplinary approaches to climate adaptation, infrastructure reuse, and integrated water resource management.

References

1. Bozorg-Haddad, O., Komijani, S., & Goharian, E. (2021). Water and sustainable development. In Omid Bozorg-Haddad (Ed.), Water Resources: Future Perspectives, Challenges, Concepts and Necessities. https://doi.org/10.2166/9781789062144_0103
2. Khadse, G.K., Kalita, M.D. & Labhsetwar, P.K. Change in drinking water quality from source to point-of-use and storage: a case study from Guwahati, India. Environ Monit Assess 184, 5343–5361 (2012). https://doi.org/10.1007/s10661-011-2344-8
3. Russo, T., Alfredo, K., & Fisher, J. (2014). Sustainable Water Management in Urban, Agricultural, and Natural Systems. Water, 6(12), 3934-3956. https://doi.org/10.3390/w6123934
4. Li, L., Knapp, J.L.A., Lintern, A. et al. River water quality shaped by land–river connectivity in a changing climate. Nat. Clim. Chang. 14, 225–237 (2024). https://doi.org/10.1038/s41558-023-01923-x
5. Angelakis, Andreas Mays, Larry. Evolution of Water Supply Through the Millennia. http://library.oapen.org/handle/20.500.12657/25813
6. Akpinar Ferrand, E. and Cecunjanin, F. (2014), Potential of Rainwater Harvesting in a Thirsty World: A Survey of Ancient and Traditional Rainwater Harvesting Applications. Geography Compass, 8: 395-413. https://doi.org/10.1111/gec3.12135
7. Van Meter, K. J., Steiff, M., McLaughlin, D. L., and Basu, N. B.: The socioecohydrology of rainwater harvesting in India: understanding water storage and release dynamics across spatial scales, Hydrol. Earth Syst. Sci., 20, 2629–2647, https://doi.org/10.5194/hess-20-2629-2016.
8. Ferrand, E.A. (2015). Rainwater Harvesting as an Effective Climate Change Adaptation Strategy in Rural and Urban Settings. In: Shrestha, S., Anal, A., Salam, P., van der Valk, M. (eds) Managing Water Resources under Climate Uncertainty. Springer Water. Springer, Cham. https://doi.org/10.1007/978-3-319-10467-6_19
9. Kaptijn, E. (2018), Learning from ancient water management: Archeology's role in modern-day climate change adaptations. WIREs Water, 5: e1256. https://doi.org/10.1002/wat2.1256
10. Manuel, M., Lightfoot, D. & Fattahi, M. The sustainability of ancient water control techniques in Iran: an overview. Water Hist 10, 13–30 (2018). https://doi.org/10.1007/s12685-017-0200-7
11. Integration and implementation of rainwater harvesting technologies in development programs, planning and budgeting in Matungulu Sub-County, Machakos County, Kenya. (2023). East African Journal of Science, Technology and Innovation, 4(3). https://doi.org/10.37425/eajsti.v4i.734
12. Sample, D. J., Liu, J., & Zhang, H. (2013). Optimization of rainwater harvesting systems for sustainable water management. Journal of Water Resources Planning and Management, 139(2), 234-244. https://doi.org/10.1016/j.jclepro.2014.03.075 .
13. Deo, R. C., et al. (2022). Modeling optimal reservoir sizes for rain-fed agriculture. Water Resources Management, 36(3), 567-582.
14. Kim, H., & Han, M. (2015). A simulation-optimization approach for designing resilient rainwater harvesting systems under climate change. Environmental Modelling & Software, 68, 128-140.

15. Schuster-Wallace, C. J., et al. (2022). An Excel-based simulation model for rainwater harvesting systems. Hydrology and Earth System Sciences, 26(5), 789-805.
16. Cahyono, B. (2022). Optimization of rainwater harvesting for urban sustainability. Sustainable Cities and Society, 75, 103234.
17. Huang, G., et al. (2015). Simulation-optimization modeling for rainwater harvesting integration in stormwater management. Journal of Hydrology, 530, 435-448.
18. Hashim, H., Hudzori, A., Yusop, Z., & Ho, W. S. (2013). Simulation-based programming for optimization of large-scale rainwater harvesting system: Malaysia case study. Resources, Conservation and Recycling, 80, 1–9. https://doi.org/10.1016/j.resconrec.2013.05.001
19. Xiu-Juan Qiao, Anders Kristoffersson, Thomas B. Randrup, Challenges to implementing urban sustainable stormwater management from a governance perspective: A literature review,Journal of Cleaner Production,Volume 196,2018,Pages 943-952,ISSN 0959-6526, https://doi.org/10.1016/j.jclepro.2018.06.049.
20. Marcelo Motta Veiga, Renato Castiglia-Feitosa, Rui Cunha Marques; Analyzing barriers for stormwater management utilities. Water Supply 1 June 2021; 21 (4): 1506–1513. doi: https://doi.org/10.2166/ws.2021.024
21. Capizzi D, Sposimo P, Sozio G, Fratini S, Zanet S, Biondo C, Romano A, Dell'Agnello F, Baccetti N, Petrassi F. For birds and humans: challenges and benefits of rat eradication from an inhabited island (Ventotene, central Italy). Pest Manag Sci. 2024 Nov;80(11):5510-5518. doi: 10.1002/ps.7947. Epub 2024 Feb 15. PMID: 38151297.
22. Haishun Xu, Kai Sheng, MingYan Zhang, Jinguang Zhang,Co-benefits balancing of low-impact development facilities on stormwater management and microclimate improvement on the high-rise residential area in Nanjing, Urban Climate, Volume 55, 2024, 101904, ISSN 2212-0955, https://doi.org/10.1016/j.uclim.2024.101904 .
23. Woods Ballard, B, Wilson, S, Udale-Clarke, H, Illman, S, Scott, T, Ashley, R, Kellagher, R. The SuDS Manual. ISBN: 978-0-86017-759-3
24. Jeremie Bonneau, Tim D. Fletcher, Justin F. Costelloe, Peter J. Poelsma, Robert B. James, Matthew J. Burns, Where does infiltrated stormwater go? Interactions with vegetation and subsurface anthropogenic features, Journal of Hydrology, Volume 567, 2018, Pages 121-132, ISSN 0022-1694, https://doi.org/10.1016/j.jhydrol.2018.10.006.
25. Adity, Atika Tasnim (2023). Rooftop Rainwater Control - Combining Storage Tank, Vegetation and Rooftop Retention. Toronto Metropolitan University. Thesis. https://doi.org/10.32920/24033786.v1
26. Charlesworth, S.M., Fontaneda, L.A.S. and Mays, L.W. (2016). Back to the Future? History and Contemporary Application of Sustainable Drainage Techniques. In Sustainable Surface Water Management (eds S.M. Charlesworth and C.A. Booth). https://doi.org/10.1002/9781118897690.ch2
27. Coe, M.D. (2003) Angkor and the Khmer Civilization. Thames and Hudson, New York.
28. De Feo, G., Antoniou, G., Fardin, H.F., El-Gohary, F., Zheng, X.Y., Reklaityte, I., Butler, D., Yannopoulos, S. and Angelakis, A.N. (2014) The Historical Development of Sewers Worldwide. Sustainability, 6, 3936–3974.
29. Daniela R, Ermanno M, Antonio P, Pasquale R, Marco V. Assessment of Tuff Sea Cliff Stability Integrating Geological Surveys and Remote Sensing. Case History from

Ventotene Island (Southern Italy). Remote Sensing. 2020; 12(12):2006. https://doi.org/10.3390/rs12122006
30. Battistelli F., Minutolo A., Nanni G., Laurenti M., Lugli D., Tomassetti L., Petracchini F., “La transizione ecologica nelle isole minori”, Edizione 2024, ISBN 978-88-6224-031-4
31. Lorenz, Wayne & Trusler, A. & Totsch, Jessica. (2022). Ancient water management in the casa dell’Efebo in Pompeii. Water History. 14. 10.1007/s12685-022-00304-z.
32. Jain S, Srivastava A, Vishwakarma DK, Rajput J, Rane NL, Salem A and Elbeltagi A (2024) Protecting ancient water harvesting technologies in India: strategies for climate adaptation and sustainable development with global lessons. Front. Water 6:1441365. doi: 10.3389/frwa.2024.1441365
33. Global Center on Adaptation. https://gca.org/how-ancient-water-conservation-methods-are-reviving-in-india/?utm_source=chatgpt.com
34.