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Circular Water Management in Public Space—Experimental Feasibility Studies in Different Urban Contexts

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Abstract: Several studies highlight the risks related to the growing water crisis, worsened by the effects of pollution, which increasingly make water sources non-potable. The current water-sensitive urban design (WSUD) approach improves resource efficiency and implements urban livability by combining natural water flows with all the scales of the urban landscape. The logistic and operational management of water disposal/treatment and distribution requires performing service design according to cities' physical and morphological features, starting from their architectural and landscape characteristics. This paper aims to prove that different landscapes can offer different inspirations and possibilities to imagine a WSUD-coherent system, fulfilling the integration requirements with the urban system. For this purpose, three case studies, differing by dimension, morphology, and urban typology, are analyzed, experimenting with circular water usage with no resource waste. This research proposes concrete actions such as conservation, restoration or addition of permeable surfaces, the installation of new accumulation and treatment systems, and the use of water-saving devices. Starting from redesigning the water system, they can also include punctual redevelopment interventions on the urban built environments and opportunities for network development with public administrations, private businesses, third-sector organizations, and end users. This experimentation has led to water savings of up to 80% of the current consumption scenario.

Keywords: water management; resource circularity; 2030 Agenda; urban regeneration

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1. Introduction

The built and paved surfaces of urban spaces are characterized by high impermeability. The low capacity of infiltration and evapotranspiration of surfaces leads rainwater to run off quickly: this is a problem during heavy rain periods, with exponentially increasing magnitude, as expected in the climate predictions for risk zones. In hot climate conditions, with low rain, drought results from global water shortages due to temperature increases, which makes some urban spaces inhabitable during some periods of the year. Even though this issue is well-known [1,2], most current rainwater management systems are neither sustainable nor adaptable to climate change [3]. Traditional rainwater drainage systems have sometimes caused high-discomfort situations, including floods and sewage water flows. Moreover, a significant water volume runs off in several urban contexts without being used. It contaminates water flows by transporting many physical, chemical, and biological pollutants, which are present in the atmosphere and on surfaces.

Existing drainage infrastructures are trench drains that move away water without retaining it, by the outdated concept according to which water represents a problem rather than a resource. Instead, the history of urban planning shows that, since the earliest settlements, mankind has preferred to build near springs, watercourses, or coasts to maximize their potential.

New approaches, including water-sensitive urban design (WSUD) [4], integrate water cycle management with the built environment, rethinking the water supply and wastewater management without affecting the local hydrogeological system. Retention, infiltration, evapotranspiration, treatment, collection, and redistribution are critical concepts at the base of WSUD (which is better known in the Middle East and Australia), while other similar approaches are developing in Canada and the United States (low-impact development) [5] and the United Kingdom (sustainable drainage systems) [6]. These concepts combine urban drainage with natural processes to reduce rainwater runoff through green-based, nature-based, and other solutions integrated into the built environment.

In Europe, this issue has been discussed since the European Directive 200/60/CE (Water Frame Directive), which marked a significant change toward a more sustainable use of the water resource, fostering, for example, technological development toward natural purification systems of domestic, agricultural, and industrial wastewater [7]. Furthermore, sustainable water resource management is now a key objective for the 2030 ONU Agenda (Goal 6), in compliance with circular economy strategies. This setting is shown by the wide use of the natural remediation of sewage water: Parco de La Gavia31 in Madrid, designed by Toyo Ito & Associates in 2013, whose system manages around 6000 m^3 of wastewater, while regenerating an arid territory with a dry river [8]. The local planivolumetric configuration of the basin also allows for improving the local microclimate and introducing various ancillary functions. The intervention in the Municipality of Gorla Maggiore in the Province of Varese (Italy) represents the first example of a spillway in a mixed network with natural remediation systems in Italy. It was realized in 2013 after choosing the location as a pilot site during a study conducted by the Po Basin Authority, which assessed its potential to resolve the water peaks during intense rainwater and the opportunities to create a new river area for the population [9].

Intervening in the built environment and rethinking it as suitable for water usage reduction can notably affect the objective of reducing the environmental impact; in particular, circular water management can be achieved by considering an integrated rainwater reuse system. Moreover, this could lead to rediscovering some elements incorporated into the built environment in different contexts. Indeed, in ages without technology systems, the need for reusing water has often conditioned construction technology. This is exemplified by ancient Roman cisterns, whose technological features have been taken on over centuries with various construction and collection systems. These have been heterogeneously integrated into the roof coverings, now characterized by innovative technologies. Natural water filtration was also a well-known technology in ancient times. In the Roman Empire, it was common to exploit the purifying potential of the cloaca maxima, discharged into the Pontine Marshes; over centuries, creating wetlands for urban use has become an increasingly widespread expedient. The earliest galleries for water drainage and supply in Palermo (12th century) are canals (known as Qanats) built to bring water to the surface from aquifers by following the morphology of the rock sediment. Using the principle of communicating vessels, they could regulate water flow from springs to the Norman kings' residences at the same height. In this context, water towers were introduced in the 15th century to regulate the hydraulic head of water flows into qanats.

Two well-known regeneration interventions of the built environment are based on water valorization: the study by Arch. Albert Cuhi in Santiago de Compostela, exploiting water as an element for territorial management, integrating vegetation and historical irrigation canals into street sections [10], and rearranging road paving in the Historical Center of Girona, based on Arch. Josep Miàs's idea to integrate an existing rainwater drainage and recovery canal system [11]. Concerning open-air canals, it is worth mentioning that Fribourg is characterized by streams turning into a suggestive urban route and an opportunity for specific rainwater treatment. An Italian city, Treviso, hosts a labyrinth of canals integrated into a medieval fabric currently in use; thanks to their excellent conservation, the mills create physical continuity between the built environment and the canals.

Various contemporary technologies take on ancient expedients, serving as natural water storage basins to reduce runoff during heavy rainfall. In several cases, accumulation systems can incorporate devices for water storage and filtration; some accumulation systems can be part of the landscape and architectural design, such as fountains or pools, and provide high aesthetic value to urban space. An example of the regeneration of an existing urban context and circularization of the water system is the well-known project of public space redesign in Potsdamer Platz, Berlin, where the roof coverings of the buildings around the square and the system of basins and canals of the square collect rainwater. Water is filtered by a system of vegetated biotopes and reused on the site for sanitary facilities and fire-fighting systems.

On the international scene, there are various innovative approaches for territorial planning rooted in environmental sustainability, water treatment, and recovery interventions. In this context, Rotterdam stands as a pioneering city, oriented toward climate-conscious governance and characterized by a long-standing history of combination between water management and design of the built environment and urban space. For example, in the water square of Benthemplein, rainwater is stored in an underground system at the Museumplain car park, which also hosts various activities for the urban community during no-rain periods.

Water management also presents various advantages regarding climate resilience, expressed at different design scales: from flood risk mitigation to rainwater collection and reuse. At the same time, water is an active subject of thermo-hygrometric well-being [12]. In recent years, various European cities (Madrid, Barcelona, Copenhagen, Berlin, and others) have experimented with models to integrate blue-green technologies into the built environment (draining paving, bio-reservoirs with natural remediation, etc.), substituting them with the so-called gray technologies [13]. Green and blue infrastructures are nature-based mitigation and climate change adaptation strategies to improve environmental and ecological quality. Among the best-known examples are the Sponge cities in China, which integrate water management in urban planning policies, implementing nature-based solutions to collect, store, and clean water. The combination of natural and artificial means allows the city to absorb and release rainwater [14]. Urban green spaces and watercourses—built wetlands, pluvial gardens, green roofs, grassy moats, and ecological parks—gradually store and release water. These are compounded by blue infrastructures and technological solutions for rainwater management through the treatment and circularization of the collected rainwater.

Numerous advantages are associated with the approaches that adopt a circular use of water: higher accessibility to water resources and water self-sufficiency; higher resilience for the presence of more permeable spaces; lower financial expense on sewage and water treatment systems; and the presence of cleaner and healthier urban areas. Moreover, the synergy between green and blue infrastructures produces multiple benefits on both the environmental footprint of cities in the territory and the resistance of the urban ecosystem, as it mitigates climate change effects.

These cases have inspired the search for a circular rethinking of water resources in two small dense urban centers with high water risk and a new hypothesis for water management in the University Campus of Palermo. The area of the three case studies has a hot and humid climate, with periods of drought throughout almost the entire year. Moreover, the urbanized area of Palermo is not prepared for the sudden climate change that is ongoing. This will result in rising temperatures on the one hand and intense rainfall situations on the other. Rain is a hydrogeological risk factor in the current precarious situation of sewers. They are inadequate for stormwater disposal because of their undersizing, poor maintenance (clogged by deposits of municipal solid waste and demolition material), and the presence of numerous sewage discharges that abusively find their way there. Moreover, today, any flow calculations for these canals result in higher flow rates for the same number of rain events than predicted during their construction because intense urbanization has made the underlying areas less permeable.

This paper aims to individuate and select contemporary technologies for circular water management that can be integrated into existing urban contexts, also with complex morphological peculiarities. The present work aims to prove that different landscapes can offer different inspirations and possibilities to imagine a WSUD-coherent system, fulfilling the integration requirements with the urban system. The goal is to ensure that both used water and rainwater, after proper treatment of filtration, clarification, and purification, as appropriate, can be reused as non-potable water for different uses and thus achieve: a decrease in the demand for non-potable water to that which is strictly necessary, economic savings, and less water flowing into the sewer system, which avoids blockages during the rainiest periods.

Case study experimentation has allowed us to define a concrete application of these technologies and verify their real long-term financial convenience. In all three cases, designing the circular reorganization of the water resource has been an opportunity to regenerate and redevelop parts of the urban fabric.

2. Method

The main operational tools for circular water management are gaining increasing diffusion. In particular, rainwater harvesting has been around for millennia, as described above, most famously in Venice. We deduced common practices by analyzing the best-known examples of virtuous water management and circular water reuse. Indeed, starting from the state-of-the-art analysis and the definition of goals, this research outlined the main aspects and operational tools for circular water management, testing them on some exemplificative case studies. The comparison of available technologies with the morphological–dimensional, material, and typological factors of the context determined the appropriate choice for each intervention site. These represent different urban contexts by dimension, morphology, and urban typology to fine-tune replicable and adaptable methodological models.

The methodology of the experimentations follows a common thread: the analysis of the current data and the relationships with the context (use of soil and hydrology); investigations on current water consumption and the typology of water supply and disposal; study of the contexts' physical characteristics, constraints, specific features, and infrastructural potential; analysis of water collecting surfaces (extension and typology), calculating the runoff coefficients, and verifying surface permeability; analyses of rainfall data; feasibility hypotheses for integrated urban networks, devices, and infrastructures, comparing their development and characteristics also in terms of integrability of the built environment, envisaging the introduction of rainwater and gray water recovery and collection systems; and study of long-term water consumption for each intervention strategy.

Hence, the research work has devised ad hoc design scenarios in exemplificative contexts, starting from the physical characteristics of the territories. The first study involved the University Campus of Palermo water cycle, aimed at transforming the current linear path into a cycle. Two more case studies are set in minor urban centers, small communities with a strong historical connotation, whose changes in management can more easily produce sustainable development. It seems realistic to hypothesize a beneficial correlation between water management strategies and prevention strategies aimed at the ethical correctness of behaviors and lifestyles affecting the reuse of resources.

In these contexts, the current scenario is the following: water from the urban aqueduct is distributed and used for civil purposes, flows into the sewage, is conveyed in the sewage treatment plant, and is finally discharged into the sea. Rainwater follows the same linear path, as it is directly channeled and fed into the sewage, purified, and released into the sea.

Hence, the goal is to allow the reuse of both wastewater and rainwater after an adequate process of filtration, clarification, and purification, making them available as non-potable water for different uses. This will lead to a decrease in water demand, with consequent savings in water and economic resources, and lower water inflow into the sewage, avoiding obstructions in the rainiest periods.

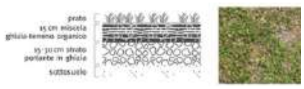
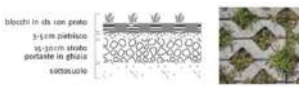
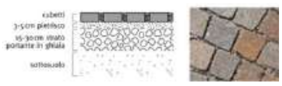
3. Main Operational Tools for Circular Water Management

Technologies for circular water management are operational tools to improve environmental quality without resource waste, providing the public-utility water supply service.

The idea is to reuse wastewater as non-potable water for different purposes, reducing the water supply to the bare minimum. The most diffuse techniques are aimed at recirculating wastewater or collecting rainwater when possible, filtering, clarifying, purifying, and storing it in a tank. The idea is to consider wastewater no longer as a problem to drive away but rather as a precious resource to collect and re-employ.

The essential actions are collection and conveyance (for wastewater drainage), treatment and filtration (to reduce water pollution), and distribution (for water supply without resource waste). Collection can be realized through SUstainable Drainage Systems (SUDS) [15], consisting of one or more surface-flow water runoff systems imitating natural drainage. For example, green roofs and green/vegetated walls fit this purpose as absorption and passage through soil and vegetation can reduce the runoff velocity and improve the water quality. Another possibility is to pave collection surfaces (building roofs, sidewalks, car garages, and streets) with permeable elements. Permeable surfaces allow water passage through an underlying gravel bed, where it can infiltrate the soil, evaporate, or be drained by the system. Permeable pavements (Table 1) and green infrastructures can provide several environmental benefits. By allowing water sedimentation and infiltration, water flowing underneath the surface evaporates and cools the external environment.

Table 1. Examples of permeable pavements (Table elaborated by Arch. Angela Battaglia).

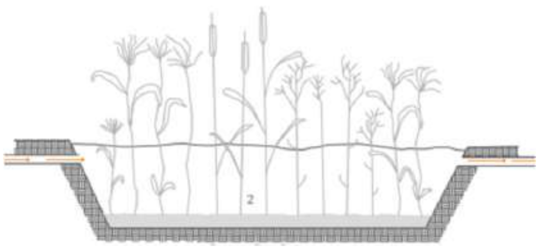
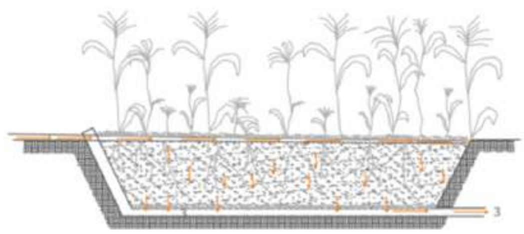
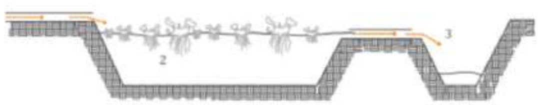
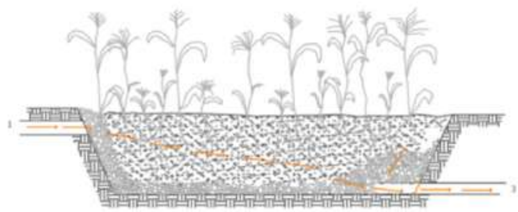
Lawns The surface consists of a layer of organic soil with grass. The ground is compacted before revegetation. They are suitable for surfaces that do not require high resistance, such as playgrounds, pedestrian routes, or occasional car parking areas.		**Cubes or blocks with large grass-covered joints** Cubes are separated by large joints, realized with spacers. The green rate reaches 35%. They are suitable for car parking, cycling and pedestrian routes, courtyards, driveways, and pathways.	
Grass-covered trails The surface consists of a layer of organic soil, mixed with cobble without binders. The surface is turned into sown grassland before being compacted. The green rate is above 30%. They are suitable for car parking, cycling and pedestrian routes, and courtyards.		**Trails** The surface is made of cobble with homogeneous grain size, without binders. They are suitable for car parking, cycling and pedestrian routes, courtyards, small squares, driveways, and pathways.	
Grass-covered concrete grids They are concrete blocks with honeycomb openings, filled with organic soil, and vegetated. The green rate is above 40%. They are suitable for car parking and access routes.		**Porous blocks** Porous blocks are laid on a gravel bed. Joints are filled with sand. They are suitable for pathways, low-traffic streets and squares, market squares, car parking, cycling and pedestrian routes, courtyards, terraces, and driveways.	
Grass-covered plastic grids They are plastic grids filled with organic soil and covered with grass. The green rate is above 90%. They are suitable for car parking and driveways.		**Cubes or blocks with narrow joints** Cubes are positioned with narrow joints filled with sand. They are suitable for pathways, low-traffic streets and squares, market squares, car parking lots, cycling and pedestrian routes, courtyards, terraces, and driveways.	

In addition to external pavements, the water-collecting surfaces of the built environment are roof coverings, and their permeability depends on each of their constitutive materials, producing a different runoff coefficient (ratio between the effective rain volume hitting the collecting surfaces and rainwater inflow). Then, morphological characteristics influence the rainwater collection capacity: the slope, exposition, and leaning elements that cover the rainwater stream. The most innovative roof coverings include the blue-green one, which several research organizations worldwide are currently studying. In Italy, among these are the University IUAV in Venice and the University of Padua, together with a network of enterprises coordinated by the company DAKU [16]. The blue-green roof is a technological infrastructure for the building's water regulation and passive cooling. The first function is performed by creating a cavity on the roof, which can contain even heavy rain; secondly, collected water is accumulated and reused to irrigate vegetation, and finally transpired through it, cooling the building. Ongoing research works are examining the hydrological performance of the blue-green roof and the plants' evapotranspiration in lowering the superficial temperature of the intrados of the roof slab, making it up to 4 °C cooler than a generic extensive green roof.

For the recirculation of collected water, it is necessary to collect it in a water tank after a preliminary selection and filtration phase. In general, this first treatment includes using a flow diverter to separate "first-rain" water, which is generally full of pollutants, from those for storage, and a filter to prevent debris and foreign bodies from entering the tank as they are collected by rainwater during its route. Some accumulation systems can incorporate water-filtering tools. The collected water is treated with a method of ultrafiltration and disinfection. This blocks soluble macromolecules and any other substance greater than the membrane's molecular size, while solvent molecules, ions, and smaller molecules can pass through.

Natural remediation (Table 2) is a natural process of water depuration through physical, chemical, and biological processes; soil also performs mechanical and chemical filtration, as the microfauna of the soil degrades the organic substances in wastewater by transforming them into nutrients for vegetal species [17]. In addition, vegetal elements provide oxygen through their roots and contribute to reducing the total amount of water sent to the sewage or watercourses.

Table 2. Examples of accumulation and remediation of rainwater. Surface-flow and sub-surface-flow natural remediation (images elaborated by Arch. Astrid Gumina).

 Free surface-flow natural remediation. System with rooted macrophytes. Filtered rainwater is channeled toward natural remediation processes using the decomposition processes triggered by the transportation of oxygen from leaves to the rhizosphere.	 Sub-surface-flow natural remediation. Vertical system (water is purified after vertical percolation). Rainwater is filtered and purified by the roots, which are anoxic, aerobic, and anaerobic. Hence, they do not allow pathogens to develop and retain heavy metals in the filling layer.
 System with floating hydrophytes.	 Horizontal-flow system.

Rainwater treatment is crucial before reuse for non-potable civil purposes or garden irrigation. In the urban space, it is possible to integrate various elements, which allow water treatment and accumulation. The following are some examples:

- Water square: urban space with variable use modality according to weather and climate conditions. Intense rain floods this space, creating a square with controlled flooding for temporary rainwater storage and subsequent supply.
- Open canals/drains for rainwater: these rainwater collection canals are an alternative to underground sewage. The presence of these elements delimits and defines the perception of urban space.
- Linear garden along the streets: characterized by flowerbeds that filtrate water through various drainage layers to direct it toward detention ponds, aiming at slowly releasing it into the underground.
- Bio-retention areas: landscape basins where vegetation improves landscape quality and retains and purifies water. These include floodable moats: controlled zones collect and store water drained through infiltration or canalization, regulating the flow toward a final sewer.
- Geo-cellular systems: prefabricated structures placed underground to store and slowly infiltrate rainwater.
- Gravel or sand filters can perform preliminary filtration for treating surface runoff water.
- Biotopes: landscapes consisting of plants assembled by ecological stability to improve water quality through natural oxygenation.
- Reservoirs, ponds, and artificial lakes: these can be designed to retain excess water. Artificial collection basins are works for rainwater storage, decantation, and infiltration. Bioretention basins are open-air and perform hydric and natural remediation functions.

4. Experimentation—Case Studies for Circular Water Management

The study presented here was developed for the University Campus of Palermo, to transform the current linear path into a cycle. It is set to achieve that both wastewater and rainwater are re-employed for non-potable uses, such as irrigation, sanitary facilities, and heating and cooling systems, following an appropriate filtration, clarification, and purification process [18].

The main strategies are rainwater recovery and treatment with a filtration and clarification system; graywater recovery through an ultrafiltration system; blackwater recovery through natural remediation tanks. The following interrelated actions are performed for cyclic water management:

- study on water and soil management (Figure 1).
- subdivision of single buildings and/or building blocks, considering the surfaces and collectible water volumes (Figure 2).
- positioning graywater and rainwater recovery and treatment systems near the individuated modules (Figure 3); positioning a natural remediation system for blackwater; changing impermeable pavements with permeable ones; using evaporative cooling techniques, adding water tanks.

The rainwater recovery system is essentially composed of two parts: the storage system consisting of a collection and drainage network and a collection tank; the reuse system that draws water from the collection tanks and distributes it into the water supply system. Thus, the reuse of recovered rainwater is performed with a “dual system” (water and reuse) that allows for differentiated withdrawal according to needs and reserves.

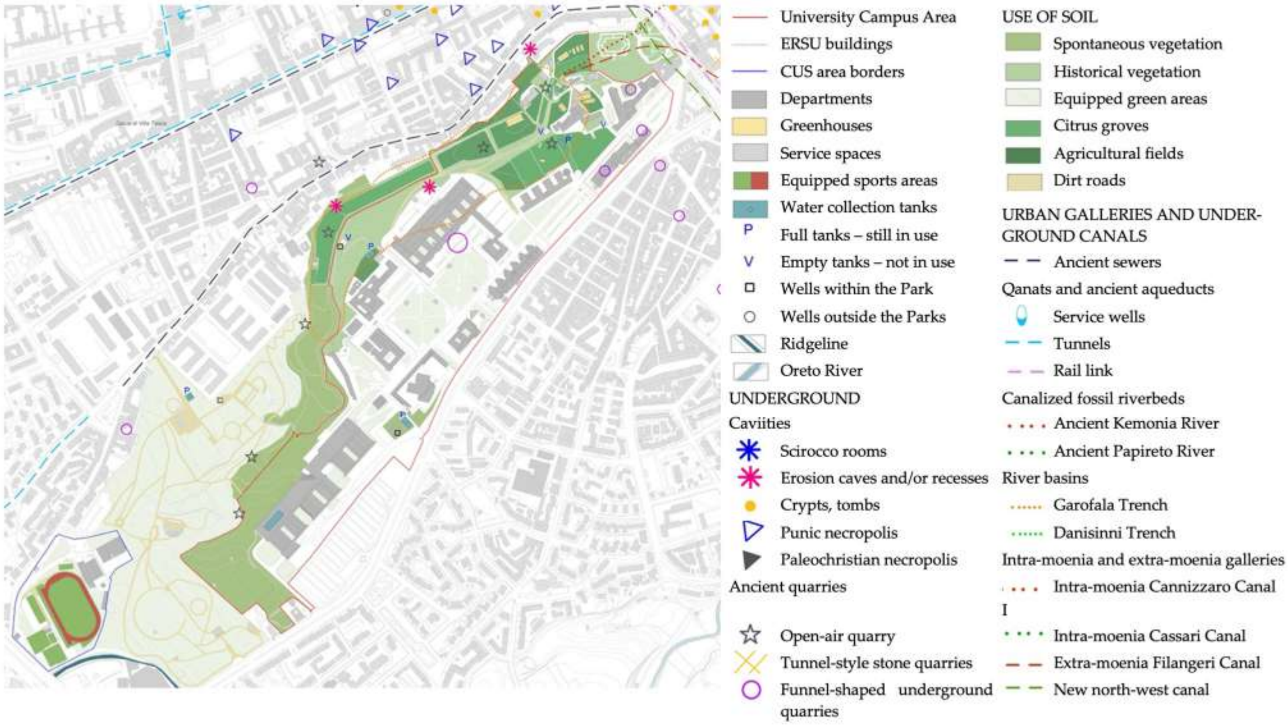
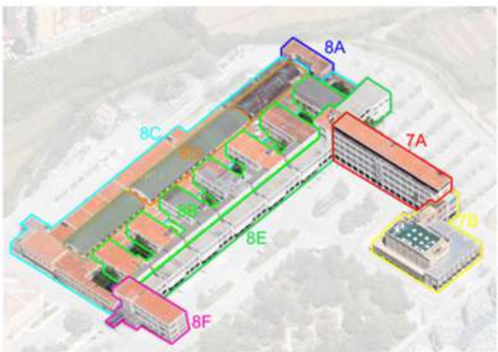


Figure 1. Use of soil, underground, galleries and canals for water distribution and drainage. The development of the city of Palermo has implied, since its origins, an intense and indissoluble relationship with the subsoil. Both geological conditions of the substrate and the anthropic activities for more than twenty-seven centuries have given rise to many underground voids, used for various purposes but always connected to surface activities. The study of the University Campus of Palermo highlighted this relationship, and the elements present within it, which have been grouped into three macro-sets: land uses; subsoil; urban tunnels and culverts (image elaborated by Arch. Angela Battaglia).



Building N.	FLAT ROOFS								
	FLAT ROOF			CUPOLA			FLAT GLAZED ROOF		
	m²	Materials	Conservation state	m²	Materials	State	m²	Materials	State
7A	1231	“Campigiana” bricks	Medium						
7B	2082	Bituminous membrane with aluminum sheet	Good						
8A	295	“Campigiana” bricks	Medium						
8B	4085	“Campigiana” bricks Bituminous membrane	Medium						
8C	10037	“Campigiana” bricks Bituminous membrane	Medium						
8D				3369	Slated bituminous membrane	Good			
8E	2843	Slated bituminous membrane	Medium						
8F	706	“Campigiana” bricks	Good						

Figure 2. All capturing surfaces on the University Campus were analyzed through a direct inspection of them to identify the materials and their general condition. In both types of capturing surfaces, i.e., ground pavements and building roofs, each of the identified materials possesses a different permeability and consequently a different runoff coefficient. The volume of collectable water can be quantified by the analysis of the surfaces. The image reports an example of the estimation of the roof coverings of one building of the University Campus (image and table elaborated by Arch. Angela Battaglia).

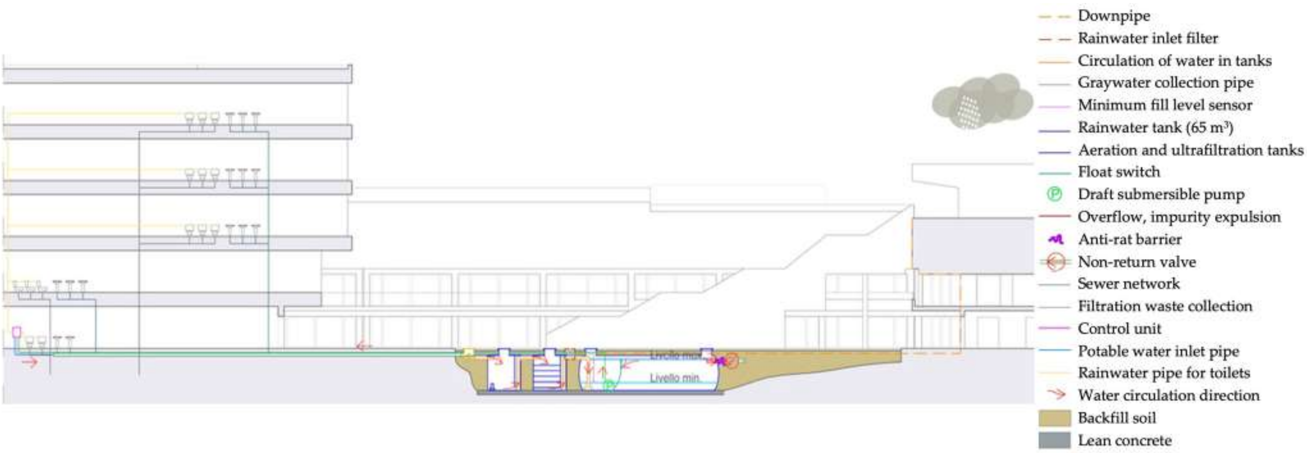


Figure 3. Sample functional section of the rainwater collection, treatment, storage, and distribution system. The image reports one of the buildings of the University Campus as an example. It is planned to recover and treat storm water through a filtration and clarification plant, recover gray and black water through an ultrafiltration plant for the former, and use natural purification tanks for the latter (image elaborated by Arch. Angela Battaglia). Livello = level.

The storage facility is sized from the calculation of the amount of water that can be captured and the estimate of water needed for activities that can be met by non-potable water (cleaning, heating, and cooling systems). For the sizing of the stored rainwater tank, these data are therefore needed: collection area (m^2) and its runoff capacity (which depends on the slope of the slopes and the type of roof); precipitation height ((L/m^2)-year or mm/year); filter effectiveness depending on the degree of cleanliness; and water needs for different uses (m^3). The sizing of the volume of the catchment tank Vser. can be carried out from the volume of capturable water Vcap., which should be related to that required to meet the water demand of the user over a year Vnec. If Vcap., is not sufficient to meet the demand, the replenishment of water from the water supply system or parallel reuse of graywater produced by users is required.

$$\text{Vcap.} = \text{ef} - \text{cd} - \text{P} - \text{S Vnec.} = \text{V} - 365 \text{ Vnec.} < \text{Vcap Vser.} = (\text{Vnec.} - 21)/365$$

where Vcap.: volume of catchable water (L/year); ef: filter efficiency, generally equal to 0.9; cd: runoff coefficient; P: average annual rainfall ((L/m^2)-year); S: water capable area (m^2); V: volume of water needed per single daily activity; 21: the factor considers the exceedance of a 3-week dry period. V is calculated from the gray water volume: Va. gr. = (n − u − V) − 365. Where n: number of users; u: number of daily uses per person; V: volume of water per single daily activity (L/day); 365: number of days in a year.

As an example, for a building having a collection area of 2592 m^2 (roof) + 571.65 m^2 (exterior pavement); a flat surface covered with concrete slabs or generic slabs (Standard EN DIN 1989-1:2000-12) [19]; under conditions of an average annual rainfall height of 707.5 (L/m^2)-year. Three underground tanks of 50 m^3 are necessary and, respectively, with dimensions: φ 243 cm; L 1116 cm; LA 265 cm.

After treatment, graywater is brought to a hygienically pure state through ultrafiltration, which allows for retaining soluble macromolecules and any substance greater than the molecular grain of the membrane. At the same time, solvent molecules, ions, and smaller molecules can pass through. A third blackwater retrieval and treatment system through natural remediation would allow for irrigating the fields of an adjacent wide green area (Garofala Trench).

Finally, it is possible to implement the production of electric energy from biomasses, reusing waste from water remediation in rainwater, graywater, and blackwater recovery and treatment systems, and the waste from agricultural activities in the nearby fields. The resulting electric energy can be used to power water pumps and water movement in the new tanks.

The desired goal is the reduction in water and economic resource consumption while achieving several environmental benefits, among which is a lower water load into the sewage during rain events, which often leads to its obstruction (Figure 4).

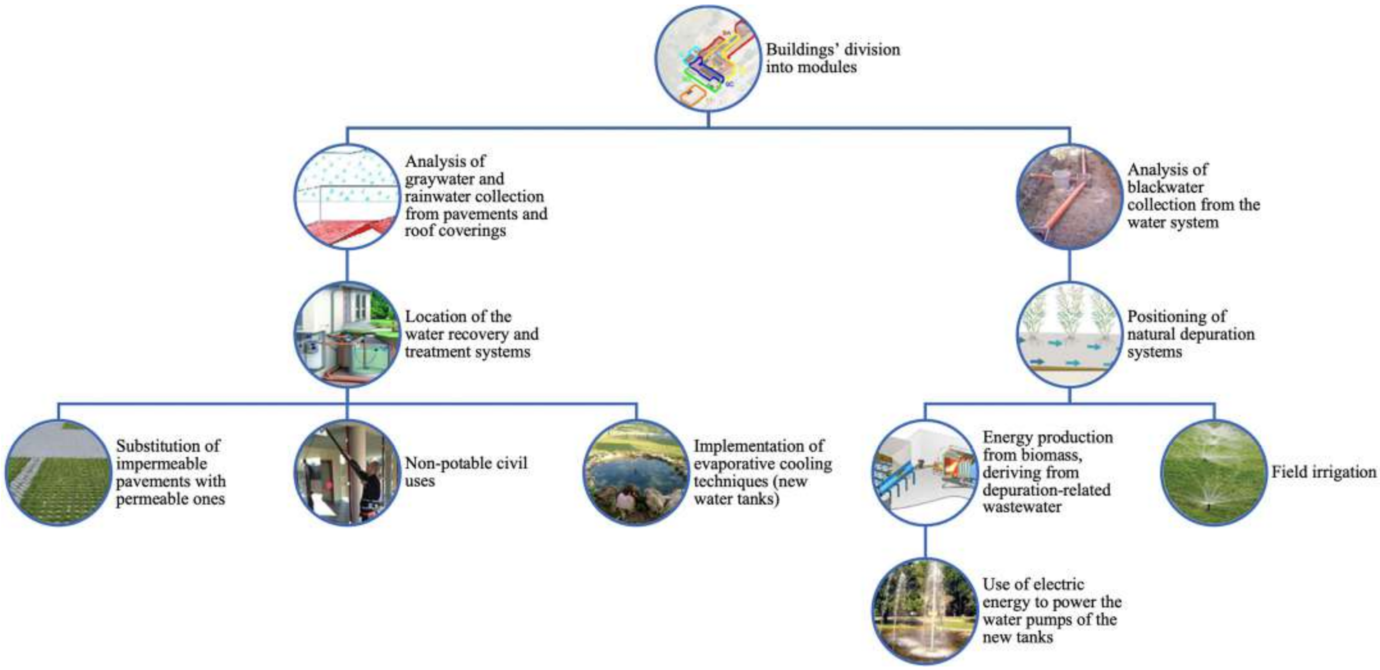


Figure 4. Circular water project of the University Campus of Palermo (image elaborated by Arch. Angela Battaglia). Rainwater recovery and treatment systems with ultrafiltration and disinfection are included.

On each building, water is collected from pavements through superficial canals and from roof coverings through exhaust ports. Then, it is filtered and fed into an underground collection tank. Water is supplied through a pump located below the water surface to collect the cleanest water layer; a self-cleaning micro-filter on the outlet of the pump also guarantees additional water purity. After this treatment, water can be reused for cleaning, supply to toilet tanks, and water heating and cooling systems.

The idea of the abovementioned interventions is to allow for wastewater usage as non-potable water for different purposes, reducing the water supply to the bare minimum. Hence, wastewater no longer has to be considered a problem to avoid but a precious resource to collect and re-employ [20].

The other two case studies focus on the circular rethinking of the water resource in two small and dense urban centers with high water risk. They are Altofonte, a Municipality with around 9000 inhabitants, and San Mauro Castelverde, a mountain village of 1600 inhabitants in Madonie Park. Both are in the Province of Palermo, and a multidisciplinary workgroup of the Department of Architecture of Palermo has hypothesized for them an alternative vision of the water cycle, including the possibility of recovering rainwater. Water could be collected from discontinuous and continuous roof coverings, permeable, semi-permeable, and impermeable pavements in both cases. The obtained volume would be sufficient to fulfill urban water demand and also allow water supply for irrigation, sports equipment, public buildings, and industrial activities [21].

The first case study, Altofonte, is characterized by high hydrogeological risk, as its territory includes countless springs flowing along the surface of the rocks, consisting of three major and other minor valleys. Hence, a huge water quantity hits the soil, creating numerous underground karstic cavities. The hypothesis is to prove the feasibility of an alternative vision of the water cycle in Altofonte, bringing to light historical elements (canals, tanks, mills) previously characterizing the urban center [22] (Table 3).

Table 3. Excerpt of the table of architectural elements related to the water path (table elaborated by Arch. Nicolò Di Matteo).

	 Baglio Romei	 Large fountain	 Fontana Borghese	 Lower mill	 Biviere	 Water tower
Construction period	19th century	19th century	17th century	19th century	12th century	19th century
Location	In a periurban area with agricultural vocation	Near the ancient spring of S. Maria di Altofonte	Near Piazza Falcone Borsellino	Near the Vallonaccio basin	Near the Maglio River basin, downhill from the town	Near the Convento courtyard
Materials	Load-bearing masonry structure with calcareous stone ashlars	Rough-hewed non-porous stone ashlars with mortar	"A cippo" vertical structure in cast iron and stone	Load-bearing masonry structure with calcareous stone ashlars	Load-bearing masonry structure with calcareous stone ashlars	Cast iron structure
History	Developed around a quadrangular courtyard, previously overlooked by workspaces, farmers' houses, and the manor house. It had a seasonal nature related to the typology of cultivation. It includes a small chapel with a wall painting depicting St. Christopher.	Placed in continuity with the spring of S. Maria di Altofonte. In the past, it coincided with the upper mill, where water was channeled into the mill system or in the spillway of the park through gate valves.	Its construction was requested by Abbot Borghese, Pope Paul V's nephew. It is part of the water path with its sequence of fountains and canals.	It is one of the three (upper, central, and lower) visible mills. Thanks to a recent regeneration intervention, it is the best-preserved one among the three. Full of milling waste, water flowed through a nearby terraced landscape, producing fertilization.	Built in the Norman period, it was an ancillary building an alleged fish farm constructed for King Roger II.	The only remaining element of the domestic water distribution system. The system was based on the concept of communicating vessels. Since it was located below the hydraulic head, water could reach all houses below the spring.
Conservation state	Terrible	Mediocre	Good	Mediocre	Terrible	Mediocre

For this purpose, it was chosen to analyze the historical elements connected to water management, systematizing them by location, material, typological and historical characteristics, and conservation state. This involved identifying architectural elements to support the overall comprehension of water distribution and disposal processes. These elements range from the 12th to the 19th century, and the following table reports their constitutive materials, the realization history, and the conservation state. The city has two springs, whose existence was strongly celebrated in the past, with the construction of several wall fountains. Valuable architectural elements include two mills. One of them has recently been subjected to recovery and reconversion works into a museum, aiming at preserving the evidence of the mills' mechanical systems. Hence, its architectural qualities can still be seen.

The first operation was evaluating the quantity of collectible rainwater in the study area with no alteration of the material and typological characteristics of roof coverings and pavements and adding minimal new infrastructures. To confine the territorial areas for rainwater collection, we focused on the altimetric aspects, individuating water routes near those points with favorable slopes.

Three devices for a treatment system have been hypothesized. In the project, they are located within the town in buildings to be regenerated, currently without a function, and with ideal morphological–dimensional and typological characteristics. In addition to providing management solutions, this proposal stands as an opportunity for reconfiguring Altofonte as a satellite of the wider metropolitan city of Palermo, contributing to the regeneration of the Hydrographic Basin of the Oreto River (Figure 5). Moreover, the vision includes a wetland for natural remediation and creating a green area for leisure through the plantation of native tree species. Finally, soils at hydrogeological risk will be consolidated by using naturalistic engineering systems.

Figure 5. Circular water project for Altofonte. The project includes the restoration of architectural elements and urban redevelopment, riverbed reclamation actions, greening solutions, interventions to the sewerage network and recovery of historic canalizations (image elaborated by Arch. Nicolo' Di Matteo).

The second case study is set in the historic urban center of San Mauro Castelverde. New rainwater and domestic water accumulation and purification methods are proposed to improve the water supply to the driest areas, minimizing waste [23].

An analysis was conducted to determine the quantity of collectible rainwater in the urban center, differentiating water-collecting surfaces by typology and runoff coefficient (ratio between the effective rain volume hitting the collecting surfaces and rainwater inflow). We identified pitched roofs with brick tiles, flat roofs and roofs with waterproofing materials, and street surfaces with variable permeability degrees (Figure 6).

The analysis of the water-collecting surfaces has provided the quantity of the water volume to be collected from rainwater to fulfill non-potable water demand in the urban area and the agricultural water demand in the periurban area. The recovery cycle can be implemented through some treatment devices: a cistern, a treatment system, and finally, a pumping system to recirculate purified graywater. In particular, three devices have been hypothesized for the treatment system, to be located in the town, which is characterized by high acclivity. These are: the filter preventing the introduction of debris and foreign bodies into the system, as they could compromise its operation; the accumulation tank; and the pumping system connected to the urban water network. The treatment is designed to be performed through natural remediation devices, mainly with water plants (unicellular algae). This is combined with the creation of new green areas, with the double function of wetlands and urban park.

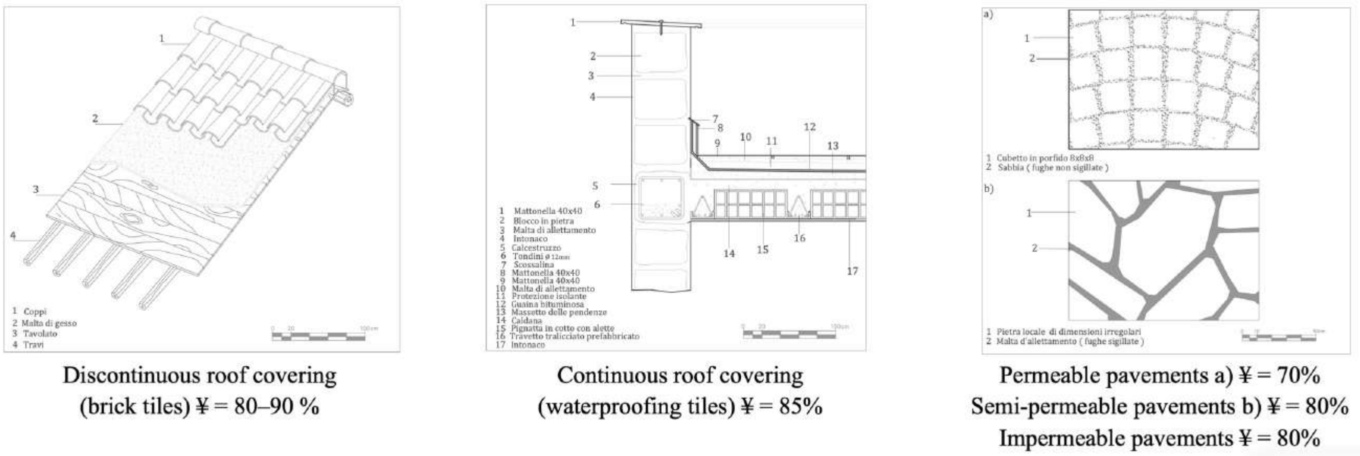


Figure 6. Analysis of the water-collecting surfaces (image elaborated by Arch. Astrid Gumina). Water-collecting surfaces are external pavements and roof coverings. According to their constitutive materials, they have different runoff coefficients.

Moreover, the project envisages a mutual aid agreement with the nearby Municipality of Geraci Siculo (Figure 7), the main potable water supplier in the hydrographic basin. In this way, the city would save primary resources as they could sell it in San Mauro at a reduced price, with purified wastewater as an exchange rate. Wastewater also represents a significant nutrient source for agricultural soils.

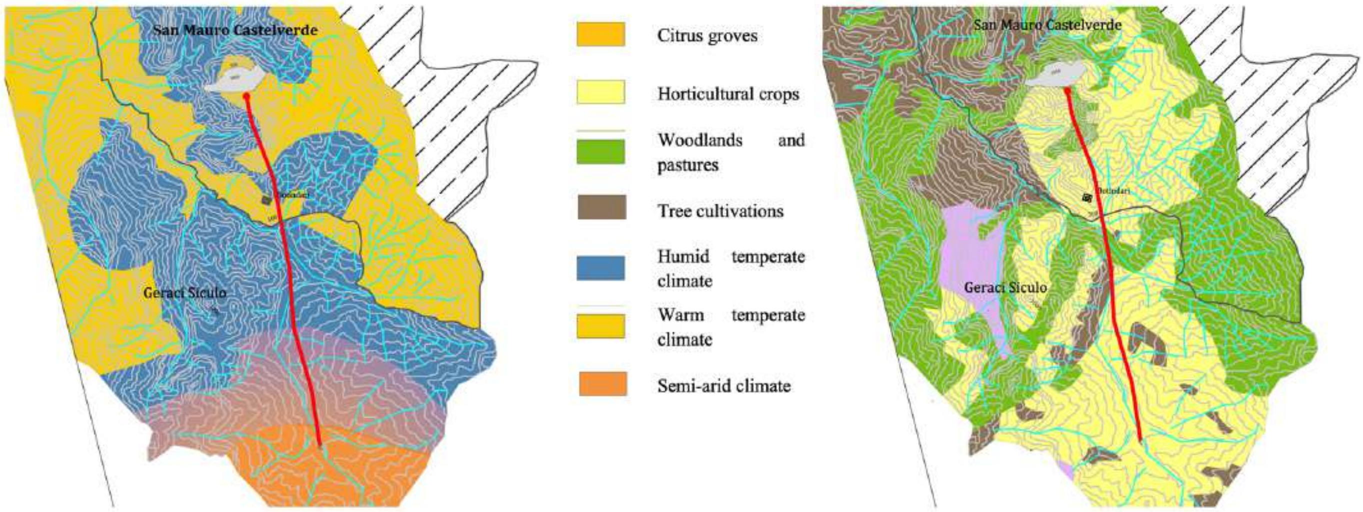


Figure 7. Hypothesis of complementary water management between nearby municipalities. Water recovered from wastewater can be used for irrigation purposes in the areas, bordering the municipal area. The red line represents the main connection between the two towns. (image elaborated by Arch. Astrid Gumina).

5. Results

In all three cases, the results are compared with the initial investigations, which involved estimating the consumption of buildings within the University Citadel, for the first case, and those pertaining to the historic center area for the other two. Specifically, water consumption data for the past three years were collected from the water meters. The analysis of consumption, both in terms of the used annual water volume and in economic terms, shows that they are clearly too high. There are several causes: carelessness is the most frequent one; other causes are related to anthropogenic factors, among which the main one is leaks from supply systems. Another cause is high land consumption, with the consequent extreme sealing of the underlying areas, which results in rapid water runoff.

Another analysis is the study of rainfall data, which has allowed us to estimate, for the Palermo area, an average annual rainfall of about 710 mm.

The normative reference for the design of the stormwater recovery systems in all three case studies was the European standard EN DIN 1989-1 of 2000-12 "Rainwater harvesting systems", which also defines the way to calculate the net intake of rainwater collected by the surface.

Considering the general strategies elaborated for the University Campus, according to the performed calculations (Table 4), the intervention would produce significant savings in terms of economic and water resources. Calculations have been performed by applying the strategies in two steps. The first step is adding water current usage devices, such as flow regulators for faucets, mechanic or electronic taps, and toilet cassettes with flow switches or dual switches. The other includes installing rainwater recovery and treatment systems, such as linear gardens along the street, grease/oil separators, underground sand beds, natural remediation systems, biotypes, and ultrafiltration systems. Regarding cost-effectiveness, with an initial expenditure of about EUR 62,000 for the acquisition of the devices, EUR 31,000 as labor cost, and EUR 11,000 for contingencies; considering the annual consumption, one could save EUR 283,862 out of the EUR 314,701 of the current state and thus be able to pay off the expenditure already in the first 5 months.

Table 4. Water consumption scenarios in the University Campus according to the strategies (Table elaborated by Arch. Angela Battaglia).

	2012	2013	2014	Planned Saving	
Current saving	395,791 m^3/year EUR 580,895	246,659 m^3/year EUR 666,218	215,254 m^3/year EUR 314,701		
Use of water-saving devices	193,938 m^3/year EUR 284,639	120,863 m^3/year EUR 326,447	105,474 m^3/year EUR 154,203	109,780 m^3/year EUR 160,498	51% of current consumption
Installation of graywater and rainwater recovery and treatment systems	38,878 m^3/year EUR 56,928	24,173 m^3/year EUR 65,289	21,094 m^3/year EUR 30,839	84,380 m^3/year EUR 123,364	80% of current consumption

The hypothesized strategy allows immediate savings of 51% on the current consumption. However, this does not mean that realizing the systems produces no advantages. Indeed, these could save an additional 80% on reduced consumption in exchange for a higher expense than installing devices. Hence, both are winning strategies: the first is designed to be implemented immediately, while the second can be enacted through programmatic phases; both would guarantee significant economic savings. In particular, according to these hypotheses, filtered and clarified rainwater can be used for cleaning, and heating and cooling systems; graywater, subjected to ultrafiltration, can be reused for supplying toilet cassettes after being stored in three accumulation tanks.

In the territory of Altofonte, in reference to the dimensioning of the vertical submersible flow depuration plant tanks to purify stormwater, the directive of Legislative Decree 152/06 was followed, which imposes, for plants with seasonal use, an equivalent size of 2 mq/inhabitant. The location of the plant and associated tanks can be traced near the arrival point of the historic canal, coinciding with the arrival point of collected rainwater.

The devised strategy can extensively fulfill historical center residents' non-potable water demand through rainwater recovery, obtaining 47,953 m^3. This also includes a surplus of almost 4433 m^3 destined for other activities such as irrigation, sports equipment, and nearby industrial activities.

The third case study proves that natural remediation hypotheses allow realizing new green areas, serving a double function of wetland with a minimum environmental impact and urban park. A rainwater collection network—with accumulation tanks in the urban fabric—conveys water to the natural depuration area, where depurated water is transported through a pumping system to a newly constructed tank. Water can be redistributed to the urban fabric; in this case, too, it fulfills most domestic water demand per person. The recovered water is estimated to be 77,019,728 L, considering a 23.5% rainwater percentage to cover 60% of the non-potable water demand. Compared to the other two case studies, urban morphology allows wider-scope hypotheses in this case, with the proposal of network water management with a nearby municipality. The remaining 76.5% of collected rainwater can indeed be destined for the irrigation of soils within the territory of Geraci Siculo. Indeed, this water contains nitrogen, phosphorus, and potassium, which serve as nutrients for crops.

6. Conclusions

Rainwater management is one of the most relevant issues to tackle in densely urbanized areas, where urban run-off (rainwater flow on surfaces) occurs on impermeable surfaces, quickly reaching the sewage networks without being filtered and retained by the soil.

The sustainable rainwater management hypothesis proposed in this experimentation is based on activating the water circle principle through various processes: the conservation or restoration of permeable surfaces, the addition of new permeable surfaces, the installation of new accumulation and treatment systems, and the use of water-saving devices. In conclusion, these experimentations have led to substantial rainwater recovery and consequent water saving up to 90% of the current consumption scenario in the first case study and up to around 80% for the other two.

The paper would be innovative because the state of the art reports some examples of circular water resource management only in new contexts; instead, service adaptation in existing contexts is certainly more complex. However, here, we demonstrate that with a few adjustments, it is possible to achieve water recovery starting from the specific factors of the existing context.

The experimentation is the result of an analytical interface interaction between available systems and different contexts: all physical interventions require space, and the appropriate one exists; the difficulty is to respect the intrinsic values of that place, especially in a historical one. The case studies, despite being just an example, already show the potential for activating planning processes around a single theme. Just an overview of the most obvious scientific factors has been given, as the topic of water recovery could and should also be addressed from a chemical, physical and biological point of view. However, we can say that the proposal, in addition to giving answers in terms of management, serves as input to tackle issues such as urban space recovery. It is an opportunity to have spaces that, in addition to functional aspects, fulfill users' needs for aesthetics and leisure.

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