

## Article

# Conceptual Study on Renewable Resource Management of Urban Water Systems in Coastal Tourist Areas

Jure Margeta

Faculty of Civil Engineering, Architecture and Geodesy, University of Split, Malice Hrvatske 15, 21000 Split, Croatia; margeta@gradst.hr; Tel.: +385-98-432-410

## Abstract

The recovery of water and other resources from urban water systems (UWSs) has long been practiced in many Mediterranean countries, but remains relatively unexplored in Croatia. In this study, the sustainable circulation processes of water, nutrients, energy, and their components in UWSs in coastal tourist areas are analyzed in order to strengthen urban systems and environmental sustainability. Dissipative structure theory is used to critically analyze the complexity and sustainability of UWSs, urban systems, and circular economy frameworks. This study is based on conceptual analysis and knowledge (experience), and the sustainability of a circular urban water system is assessed based on circular thermodynamics. This study examines the core concepts of circular urban water systems as a local resource for nutrients, water, and energy, integrating approaches that strengthen resource recovery concepts. Systemic urban climate adaptation and circular urban systems have been adopted as interrelated strategies for resilient cities, focusing on closing resource loops while building resilience to climate impacts through whole-system approaches. This framework moves beyond single solutions, connecting urban planning, energy, water, waste, and social factors to incorporate green and low-carbon developments into cities. It was established that the principle of integrated resource management lies at the heart of effective water, energy, and nutrient management in coastal urban areas, which treats entire urban life support systems as an interconnected system. Such systems increase the efficiency percentages of water, nutrient, and energy recovery while minimizing sludge volume and system entropy, thus supporting the tourism economy and low-carbon development.

**Keywords:** concept study; circular economy; urban water system; integrated resource management; circular thermodynamics; tourist areas



Academic Editor: Sabina Rakhimbekova

Received: 31 December 2025

Revised: 4 February 2026

Accepted: 5 February 2026

Published: 2 March 2026

**Copyright:** © 2026 by the author.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

## 1. Introduction

Projections show that two-thirds of the world's population will live in urban areas by 2050, creating a huge demand for reliable and sustainable urban water systems (UWSs) [1]. Coastal cities are growing rapidly, with about 15% of the global population living within a few miles of a coast due to economic hubs, job opportunities, trade, recreation, and access to nature [1]. Such urbanization and demographic shifts have led to increasing pressure on coastal environments, pollution, and resources; increasing demand for better planning regarding vulnerability to climate change and especially sea level rise; and water, food, and energy deficits. To sustain livelihoods, relevant urban and capital structures must evolve into less-dissipative systems to enhance adaptation. This requires integrated

resource management (IRM), sustainable financing, and long-term planning that accounts for climate change and resource depletion over the coming decades and even centuries.

Croatia's coastal area is not an exception in this regard but, rather, an extreme example. Seasonal demand is increasing (energy and matter input), as is seasonal waste and related pollution (energy and matter output). Thus, the imbalance between seasonal and off-season demand and waste loads is increasing, which creates additional system dynamics and stresses on the natural and urban environment and infrastructure, which are degrading over time. Summer tourism in Croatia is a major industry and economic sector, largely concentrated in the coastal areas and inhabited islands along the Adriatic Sea. It has historically represented a large portion of the country's economic output (GDP), routinely reaching 10% to 15% of the total GDP [2]. Thus, socio-physical and economic problems are becoming increasingly complex and difficult to solve, as both external climatic pressures and internal socio-economic pressures are accelerating while adaptation is delayed, making the entire socio-economic system increasingly vulnerable. Sea level rise, increases in climate extremes and variability, and the limited capacity of water, food, and energy supply chains are priorities for adaptation. A suitable response to the current situation and trends is based on the IRM framework, incorporating circular economy (CE) strategies and systemic urban climate adaptation.

At present, the difficulties in implementing the circular economy in urban water systems in tourist cities in Croatia are mostly organizational: a lack of/insufficient cooperation and an underestimation of long-term local and global benefits. A specific problem is the technological aspect of large seasonal oscillations in the functioning of the urban system (on-season–off-season) [3]. As these oscillations are very significant, especially in smaller settlements with large tourist capacities, the possibility of establishing a rational, sustainable conceptual and technological solution is questionable. Therefore, it is necessary to examine new, more integrated circular concepts and specific elements, such as longer-term storage facilities and an appropriate interpretation of sustainability, as well as to further develop arguments, frameworks, and interpretations. This work aims to achieve this, in order to extend our understanding by clarifying concepts and theoretical structures.

Systemic urban climate adaptation is a holistic approach to making cities resilient to climate change by transforming interconnected urban systems (infrastructural, social, ecological, and economic) simultaneously, rather than tackling issues in isolation. It is a cross-sectoral IRM approach to tackling climate change and resource depletion by integrating solutions across technology, governance, environment, and society, moving beyond siloed, reactive measures to build broad, anticipatory resilience. It recognizes climate impacts and resource depletion as interconnected challenges requiring unified, multi-level responses, focusing on long-term, integrated strategies like nature-based solutions, green spaces, resilient infrastructure, equitable development, CE, and community involvement to create robust, system-wide preparedness and avoid maladaptation. Such an approach ensures that actions create positive feedback loops, maximize benefits, and avoid unintended negative consequences, which entails the application of circular urban systems (CUSs).

CUSs are city models designed to eliminate waste, pollution, and resource depletion by keeping products, materials, energy, water and nutrients in use at their highest value for as long as possible, essentially closing material loops through reuse and recycling, all while regenerating natural systems and promoting sustainable living, powered by renewables and collaboration between citizens, businesses, and government. This strategy contrasts with the traditional linear “take–make–waste” model, creating resilient, regenerative urban environments with the following goals: reduce the extraction of all resources, enhance resilience, and improve health and economic opportunities. This strategy involves implementing circular principles across all city functions, from energy and water to transport

and buildings, by studying resource flows (matter and energy) in urban metabolism to identify opportunities for closing loops and improving efficiency, as well as the development of sustainable infrastructure using renewable energy and efficient integrated water management; i.e., circular urban water systems (CUWSs).

A CUWS is a regenerative approach representing a shift from a linear model to a closed-loop system, focusing on reusing and recovering resources (water, nutrients, energy) within cities to minimize waste; reduce reliance on fresh water, energy, and nutrients; and enhance urban resilience through technologies such as rainwater harvesting, greywater recycling, and nature-based solutions (bioswales, green roofs). It also considers the reuse of wastewater following advanced treatment (sludge), nutrient recovery, and green energy (biogas) recovery via anaerobic digestion. Such systems integrate water, wastewater, and stormwater systems to create healthier environments, boost local economies, and build sustainable, climate-ready cities by integrating water management with urban design and river basin sustainable development.

In this study, a sustainable development measurement model is established based on dissipative structure theory. A city (CUS), as a dissipative structure, can be considered a self-organizing system that maintains internal order through the constant exchange of energy and matter with its surroundings, existing in a state of thermodynamic non-equilibrium. This is also true for CUWSs—to function as dissipative structures, they must be open systems that exchange energy, matter, and information with their (urban and natural) environment. This involves both physical constraints and the social ability to modify the environment, leading to more complex, self-sustaining structures such as those seen in biological and social systems. Examples include the development of ecosystems, urban environments, less-dissipative supply chains (e.g., of water, food, and energy), and the ability to adapt to both internal and external change. Such frameworks simplify the assessment of complex circular systems and their contribution to achieving sustainable development goals. The proposed concepts represent a shift from mere compliance with discharge standards and other initiatives to resource recycling, energy acquisition, and the realization of long-term sustainable green and low-carbon development.

An urban water system can be considered a dissipative structure because it maintains order and complexity through a continuous flow of energy and water, exporting entropy to its environment. This system is open and far from thermodynamic equilibrium, with human activities like cooking, bathing, and irrigation (social dissipation) and natural processes like evapotranspiration from surfaces and buildings (physical dissipation) driving the conversion of liquid water to water vapor, which is then exported to the atmosphere with heat. In other words, an urban system maintains its internal order and complexity by importing energy, food, and materials from the environment and exporting waste and heat. In such an environment, the socio-physical dissipative adaptation of urban and tourism systems becomes increasingly complex, and must account for the dual pressure of extreme internal seasonality and persistent climate change. For example, complex structures (regarding, for example, accommodation, catering, and attractions) and organizational structures require large amounts of energy, water, and food, which are eventually dissipated as heat and waste. Hence, the concept of a city as a dissipative structure raises crucial questions about sustainability.

The solution offered in this paper is based on the planning and application of a UWS as a less-dissipative structure using the CE strategy. This allows us to tackle water, food, and energy sustainability challenges using a systemic and transformative approach to deliver water supply, sanitation services, and urban flood protection in a more sustainable, efficient, and resilient manner. Moreover, a new World Bank report titled *Water in Circular*

Economy and Resilience (WICER) aimed to establish a common understanding of circular economy and resilience in the urban water sector [4].

To verify this concept, it is necessary to conduct integrated climate vulnerability assessments (IVAs) [5]—systematic processes that evaluate how climate change impacts a system by analyzing its exposure, sensitivity, and adaptive capacity across multiple sectors and scales. These assessments are used to inform climate adaptation strategies by identifying which human security issues (food, water, health) are most affected and by whom, following which a response can be developed and improved. Previous studies have tended to combine “top-down” quantitative data (like climate models) with “bottom-up” qualitative data from local knowledge and practices. This study examines circular concepts within particular water/wastewater, urban water, and urban systems, considering their elements and relationships, to offer new interpretations based on circular thermodynamics. A bottom-up approach allows for easier analysis of smaller systems and thus facilitates their integration into more complex systems (CUWSs) and then into CUSs, thereby capturing the water, wastewater, and stormwater parts of the emergent circular system. Circular thermodynamics have been previously considered to assess the sustainability of organisms and systems [6]; thermodynamic principles have been applied to cyclical processes, especially in living organisms or sustainable systems, with the aim of closing loops, focusing on energy/matter flow, minimizing entropy production (like in living things), and ensuring efficient resource use, contrasting with linear models.

Lifecycle sustainability assessments of urban water systems are typically conducted to evaluate all environmental, social, and economic impacts, both negative impacts and benefits. These assessments implement thermodynamic functional units, resource availability, and exergy analysis. Water, nutrients, and energy are typically used to quantify and evaluate resource consumption; however, some applications have moved beyond simple resource accounting to assess true sustainability by tracking irreversible losses (entropy generation) throughout resource/service lifecycles, enabling the resource recovery efficiency of different circular systems to be evaluated. Key quantity aspects include inputs (e.g., raw water, materials, and electricity as exergy) and outputs (e.g., reclaimed water, nutrients, useful energy, sludge, waste, and carbon emissions), as well as the identification of thermodynamic inefficiency hotspots (exergy destruction). Qualitative comparative analysis of circular concepts has been conducted to systematically analyze combinations of conditions (factors) that lead to specific concepts and outcomes.

Systemic climate adaptation and the implementation of circular urban systems are intertwined strategies for resilient cities. By closing resource loops and adopting whole-system approaches—such as water reuse, biogas and nutrient recovery, regenerative building design, and green infrastructure adoption—cities can simultaneously reduce emissions, boost sustainability, and ensure equity. These methods transcend isolated solutions, integrating urban planning, energy, water, waste, and social factors to transform cities into adaptable, low-carbon, and resource-efficient environments. This study focuses specifically on circular urban water systems within the context of coastal tourism. Two main novel frameworks are proposed: (i) the application of dissipative structure theory to circular UWS development and assessment; and (ii) a circular thermodynamic approach to sustainability assessment (entropy generation). The development path of the water–energy–food nexus and resource recycling for urban water systems is key to solving the water, energy, and nutrient dilemma of coastal areas and promoting green and low-carbon development, strengthening the sustainability of the environment, the tourism economy, and society in the long-term. Circular concepts provide long-term stability and reliable water volume, energy production, and nutrient supply.

## 2. Materials and Methods

### 2.1. Methodology

This study explores the development of UWSs in tourist areas and cities to obtain deeper insights into complex circular urban water systems and guide future research and applications/practice. This study contributes the following:

- Develops a framework for understanding the circulation of urban water system resources and proposes interventions to improve circulation and system outcomes.
- Reviews the literature on UWS and UWS resources.
- Conceptualizes a research framework.
- Analyzes theories and models that affect resource circulation in UWSs.
- Explores the effectiveness of different interventions to enhance circulation performance.
- Provides a theoretical foundation for understanding the circulation of urban water resources.
- Proposes a framework for future research and practice.

The application of circular economy concepts to UWSs was critically analyzed to determine possible circulation advantages and limitations.

#### 2.1.1. Theories and Models

The concepts explored in this paper are analyzed using dissipative structure theory to evaluate the complexity and sustainability of UWSs and urban systems (USs). Dissipative structures (DSs) are organized systems that maintain their order by dissipating energy, water, and matter. Sustained by non-equilibrium processes, examples of such structures include human societies, cities, and UWSs. Here, this framework is used to critique and enhance the circular economy's feasibility, arguing that it may face limitations due to the fundamental entropic nature of urban and UWS processes, and the need for continuous and sustainable energy and material inputs.

This study analyzes sustainable circulation processes and the components necessary for IRM in coastal tourist areas. It examines how reinforcing the sustainability of water, food, and energy circulation processes enhances the sustainability of urban systems and the environment. For example, water storage is considered a dynamic open system that maintains its organizational structure through the continuous exchange of energy and water with its surroundings. It dissipates excess energy and water to remain stable in a state far from equilibrium, serving as a typical dissipative structure. Such a system relies on a continuous flow of energy and water, rather than a stored reserve (i.e., static stock for future use). Therefore, in a circular economy, the urban water system must be treated as a socio-physical dissipative structure that strengthens the resilience of the urban system. Principles characterizing less-dissipative structures (LDSs) must then also be applied to build human systems that behave more like resistant, self-sustainable natural ecosystems.

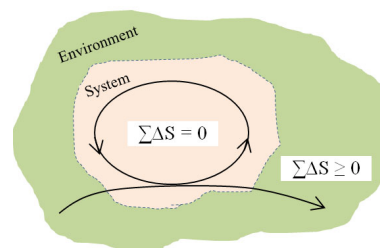
The sustainability of a CUWS is assessed using circular thermodynamics [6]. As open dissipative systems, CUWSs and CUSs are designed to use and store energy and water in an efficient manner, while maintaining their structure, functions, and a stable internal environment despite changing external conditions, both urban and natural (e.g., climate-related). Although the internal state is not static, it can be kept in a stable range through constant adjustments to external and internal changes. Mechanisms such as circulation (negative feedback loops) help the system to detect and correct deviations from its stable state, providing the system with dynamic stability and an autonomous adaptation capacity to reduce its sensitivity and vulnerability. With such capabilities, the output processes can transfer energy and water directly to those requiring it. This may be achievable through the integration of related circular water dissipative structures (infrastructure) into an IRM system to coordinate various resources for sustainable outcomes.

The significant space–time differentiation of coastal urban systems is directly proportional to its resources' (water, food, energy) storage capacity or residence time. Therefore, any change in demand or supply threatens the stability and sustainability of the urban system and economy. When balanced, the system's organizational structure is maintained and dissipation is minimized; that is, entropy is output to the surroundings, which could be considered part of another circulatory system. This implies that waste from one cycle is a possible resource for another cycle.

Input–output thermodynamics enable the tracking of energy and matter transformations, ensuring that what goes in must come out in some form, recognizing that outputs often emerge as less useful energy or waste. This provides an accounting framework (mass/energy balances) for analysis of physical systems such as DSs, which transform inputs into desired outputs while respecting the fundamental conservation of energy laws, in that input energy is not lost but changes form (i.e., energy in = energy out + energy stored); this also applies to matter/water. Thus, the total matter in a system remains constant, and what comes in must either leave or accumulate.

The Second Law of Thermodynamics states that the efficiency of a system (entropy) is Useful Output Energy (matter)/Total Input Energy (matter). This law implies that no process is 100% efficient; some energy is always dispersed as unusable heat, increasing entropy (disorder). This helps us to evaluate the direction and rate of energy and matter flow and thus determine a system's sustainability. The entropy of an open system ( $dS$ ) changes through interchanges of energy and matter with the environment ( $d_eS$ —external entropy) and through increases in entropy in the system itself ( $d_iS$ —internal entropy) as a result of unavoidable inner processes ( $d_iS > 0$ ); namely, we have that  $dS = d_eS + d_iS$ .

Exchanges of energy and matter with the environment can be either positive or negative. Thus, the entropy of an open system decreases because associated processes produce positive entropy in other parts of the environment (other systems), as the internal entropy change is positive ( $d_iS > 0$ ). Therefore, a sustainable system approaches an ideal dynamic balance of zero-entropy production (Figure 1).



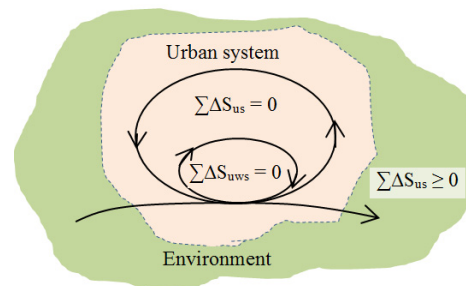
**Figure 1.** Zero-entropy model of ideal sustainable open system (arrows—energy and matter flow), adapted from [6].

The simple equation  $\sum \Delta S = 0$  inside the cycle states that there is overall energy and matter conservation, as well as compensation entropy such that the system's structure is maintained and dissipation decreases to zero, while the dissipation that must be exported to the system's surroundings is also minimized,  $\sum \Delta S \geq 0$ . Internal entropy compensation and energy and matter conservation imply that positive entropy generated somewhere is compensated by negative entropy (or entropy decrease) elsewhere within the system over a finite amount of time.

#### 2.1.2. Effectiveness of Different Interventions

Circulation allows UWS activities to be interconnected such that the resources generated can be transferred between urban water systems, as well as with other urban systems (solid waste, energy), thus strengthening urban socio-economic sustainability and stability.

The symmetric coupling of processes within a system under constant energy and matter flux can be optimized to produce stable, predictable, and uniform behaviors. By strengthening these internal links, the system becomes a less-dissipative system, minimizing matter, water, and energy losses. Adapted cycles span multiple relevant spatio-temporal scales, the totality of which constitute the CUWS within CUS. Every constituent cycle should reflect the properties of the whole. This integrated model is achieved through the repetition of fundamental rules that reveal the intricate structures hidden within the CUWS, from which emerges an unfragmented UWS. Coupled forms of systems and cycles are created using the IRM framework to support sustainable growth and development (Figure 2), with CE strategies built into the IRM system for better efficiency.



**Figure 2.** The flow of coupled resources in a US and UWS in a sustainable system (arrows—energy and matter flow), adapted from [6].

A sustainable UWS maximizes non-dissipative cyclic flows of energy and matter and minimizes dissipative flows. Maximizing non-dissipative cyclic flows increases the energy and matter storage capacity, which also affects the following: carrying capacity; the number of cycles in the system; resource and energy use efficiency; space–time differentiation, which translates into sustainability; balance in flow of resources and energy; and reciprocal coupling processes. Dissipation minimization reduces entropy production. Thus, the energy and matter output/input ratio provides a good indication of sustainability and system efficiency.

In a UWS, matter comprises essential components including clean water and nutrients (N, P), as well as various pollutants (heavy metals, organics, pathogens, pharmaceuticals) deriving from residential, industrial, and stormwater sources, all cycling through complex water infrastructure, circular systems, and interconnected natural systems (coastal river basin). Cycles provide urban systems with dynamic stability and autonomy. This applies in social systems, which are also open systems that exchange energy, water, and matter with the environment. When societies lack water, food, energy, or effective governance, they tend toward disorder/chaos; i.e., societal entropy increases. Hence, the entropy method provides an indicator for objectively assessing the sustainability of coastal nature, society, and economy. Adaptive technologies can be employed to neutralize (entropic) perturbations, enhance output from the original change process, and reduce or even eliminate changes that bring the system back to equilibrium. Therefore, in human society, socio-physical dissipative systems (CUWSs, CUSs) ensure livelihood sustainability.

In the coastal areas of Croatia, the dominant linear input–output system continuously expands, swallowing up the earth’s resources and laying waste to everything in its path. There are no closed cycles to hold resources within or with which to build stable, organized social or ecological structures. This constitutes the essence of the country’s seasonal boom-and-bust tourist economy. Conversely, a zero-entropy CE is embedded deep within a biogeophysical environment. Spatio-temporal structures are designed to store and mobilize renewable energy and matter, adding value in various ways, such as in primary productivity (from sunlight and photosynthesis), secondary productivity (primary con-

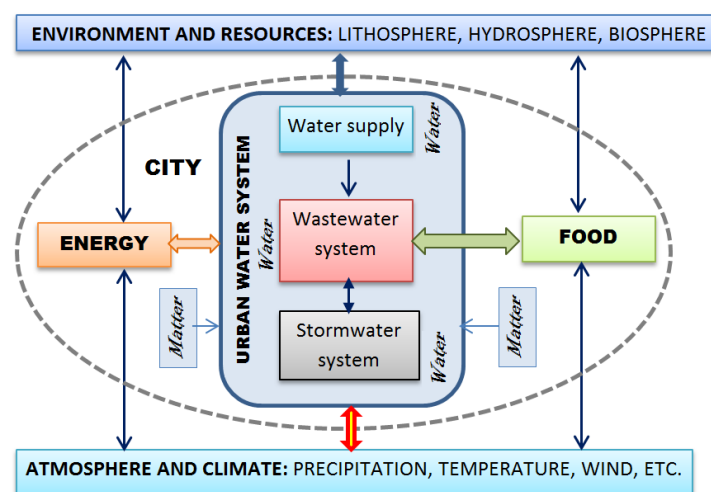
sumers), and tertiary productivity (higher consumer productivity). To achieve sustainable outcomes, IRM must be used to facilitate efficient coupling of the natural biogeophysical and urban environments with urban socio-physical dissipative structures. This synergy defines circular dissipative system adaptation. In coastal cities, the sea and coast are key socio-economic resources whose preservation largely determines the sustainability of the local community. In essence, circular dissipative system adaptation describes how life and complex structures arise and persist. Through continuously processing energy, water, and matter, these systems can be optimized to minimize entropy production. To sustain such functions, the CUS must implement stable circular patterns and optimize functions by balancing energy, water, and matter inputs with dissipative losses.

## 2.2. Urban Water System Resource Recovery Potential—Literature Review

In order to better understand the issues addressed in this study, the following subsections present basic knowledge regarding the characteristics of water, wastewater, and stormwater urban infrastructure and systems, their interrelationships, and their potential water, nutrient, and energy resources.

### 2.2.1. Urban Water System

The main parts of a UWS—water supply, wastewater management, and stormwater control (Figure 3)—are hierarchically organized based on the movement of energy, water, and other matter through it. These components form an interconnected urban water cycle with the city's water resources system through its input and output structures [7].



**Figure 3.** UWS, environment, and vital resources.

Water supply systems supply cities and people with potable water at adequate pressure. Such systems can be analyzed as a dissipative structure because they are open, complex systems in a state far from equilibrium. They are organized by network layout, treatment processes, and distribution patterns, maintaining internal order through continuous energy and water exchange (input) to prevent stagnation and maintain flow. However, the system produces entropy through energy transformations (friction, pumping) and water losses. It aims to move towards self-organized sustainability or, conversely, potential collapse if it fails to adapt to internal demand shifts and external climate pressures.

Urban wastewater systems collect and transport wastewater (domestic, industrial) through sewer networks to treatment plants, which remove pollutants before safe discharge or reuse, protecting human and environmental health [8]. This system functions as a complex, open system (an “urban metabolism”) that constantly exchanges energy, water, and

matter, exhibiting characteristics of dissipative structures. Such a system continuously uses anaerobic and aerobic processes within the network and at treatment plants to transform waste into different forms (treated water, sludge, energy, and nutrients) while moving away from chaotic states towards new, ordered states—even sustainable states, if possible. For such systems to remain far from equilibrium, they require continuous energy and material inputs (electricity, chemicals) and constant management to maintain their functions and prevent system collapse resulting from the pollution of urban areas, water resources, and the sea; overflowing sewers; and other negative consequences to humans and the environment. As open systems, they constantly take wastewater (water, matter, and energy) and output products requiring further processing as well as treated effluent, sludge, heat, CO<sub>2</sub>, and methane, recycling nutrients and energy recovery. Without appropriate input (management failure), the system rapidly shifts to chaotic states (pollution, flooding).

The water supply and sewage systems are hierarchically organized. Raw water is treated to meet drinking water standards. After use, drinking water becomes wastewater that flows into wastewater sewers and then into a wastewater treatment plant, where it is purified and then released into water resources. In classical linear systems, this is characterized by unidirectional flow. While the volume of water may be time-varying, the one-way flow moves from water resources to the city and back to the environment as treated waste. The flow of water within the system is influenced by the city's water consumption regime/dynamics. The balance of water flow and quality as well as water pressure in the system are controlled and managed. In water supply systems, service reservoirs are crucial water storage facilities, usually storing treated drinking water near consumers to balance supply–demand flows, maintain system pressure, and provide emergency reserves; for example, for firefighting.

Energy is necessary to transport water from the environment to the users and back, as well as to treat water and wastewater. Transportation is primarily realized by pumping stations and gravity. Differences in system elevation and the distances between water intakes, water users, and wastewater treatment plants can be significant. Consequently, modern water pressure systems rely on electrical energy for the transportation and distribution of water and, thus, are highly energy-intensive. Energy costs are a huge factor in operational budgets, depending on the topography of the system (33–80% of non-labor costs). Without electric energy, modern systems cannot function and are not operationally sustainable [9].

Classic stormwater sewerage also features a one-way flow. The input to the system is rain over the city surface and the associated marginal catchment area, from which the water flows downhill into and through the city. This system acts like a dissipative structure by converting excess water energy (kinetic and potential) into turbulence, heat, and sound, preventing erosion and reducing the risk of downstream flooding. System components (manholes, cascades) break down high-energy flows into turbulent, lower-energy flows, reducing water velocity and power. By converting high-grade energy (flowing water) into disordered forms (heat, turbulence), these systems increase local entropy, allowing the system to maintain its organizational structure and manage water without failures. Essentially, the system scatters destructive energy, allowing the urban environment to function better under stress from rainfall. The runoff process is intermittent (stochastic) and largely uncontrolled, determined by the intensity of precipitation, the catchment area characteristics, and the gravitational potential energy of the drainage system. Therefore, it is very susceptible to climate change. To manage flow, it is often necessary to build retention basins and pumping stations. The stormwater system also includes a treatment plant for purification of the collected water [8]. As the system only moves water during rainfall, its consumption of electrical energy is not significant.

An urban water drainage system can be structured as one of three types: Combined, separated, or semi-separated. In a combined system, one pipe carries both sewage (foul water) and stormwater runoff. It is a simpler design, but is prone to overflows during heavy rain as wastewater and stormwater are drained through the same channels. These are typically found in historical urban centers, and are simple and cheap to build if the wastewater discharge will not be treated. Otherwise, due to the variable water flow and water composition, their construction and treatment costs can be high, and their operation can be difficult. Such a system is not very suitable for resource recovery, primarily due to the varying water volume and quality (dry vs. rainy) and the treatment cost. These systems are sensitive and vulnerable to climate change, requiring more complex adaptation measures; therefore, such systems are no longer being built [9].

Separate systems consist of two distinct pipe networks: one for wastewater (foul) and another for stormwater. This setup prevents combined sewage overflows and water resource pollution, making these systems suitable for resource recovery. A sub-variant involves the implementation of semi-separate (partially separate) systems of varying complexity, affecting the possibility of resource recovery and climate change adaptation. Such systems blend separate and combined sewers, carrying most indoor wastewater and some stormwater (roofs gutter) through one pipe to the treatment plant, and large stormwater volumes are carried through separate drains. This is a suitable and practical system for sparsely populated areas. In another type of semi-separated system, the most polluted stormwater is drained together with wastewater system to a wastewater treatment plant to prevent pollution discharge in the environment. This system is suitable for densely populated areas that do not prioritize resource recovery, due to the diverse quality of and toxic substances (heavy metals) in stormwater. The type of sewage system in an urban environment significantly influences the urban water regime and, thus, the quality and availability of resources, which affects the implementation of circular systems. In order to better protect the environment and create ideal conditions for the implementation of circular concepts—such as enhancing the climate change adaptation capacity of resource recovery systems—the EU Waste Water Directive has stipulated that all sewage systems must be separate. For this reason, all combined systems are gradually being transformed into separate systems.

The UWS is a typical example of an input–output system (Figure 4) [10]; that is, an open system in which low-entropy resources are transformed through movement and use in the urban metabolism into polluted high-entropy resources that negatively impact the environment and people. Entropy increases with the movement of water from the inlet to the outlet. Through resource recovery and water reuse, the system's entropy is reduced, which strengthens the sustainability of the urban water system, city, and natural environment; in this way, the UWS aims to enhance security and reduce the disorder that humans create in the environment through their existence.

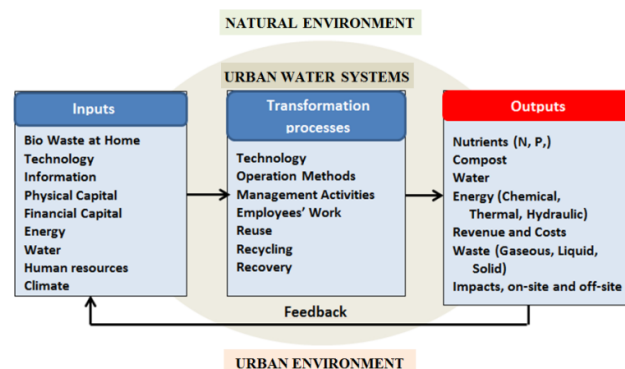


Figure 4. Input–output urban water system.

### 2.2.2. Urban Water System Resources

The main resources of a UWS are water, nutrients (nitrogen, phosphorus), chemical energy, thermal energy, hydraulic energy, and various substances, depending on the composition of wastewater and stormwater. In UWSs, matter constitutes essential goods like clean water and energy, as well as diverse pollutants (pathogens, organics, heavy metals, pharmaceuticals, suspended solids) from residential/commercial, industrial, stormwater runoff, and mobile sources, alongside nutrients (N, P) and emerging contaminants (gasoline additives, microplastics, PFAS), which all flow and circulate through the urban water infrastructure (pipes, channels, treatment plants, pump station, retention basins) and associated natural systems, thus affecting the resource recovery potential. The quantity and composition of the water vary over time and space and depend on the characteristics of the climate and city, as well as the activities that take place in the city, around the city, and within the UWS. Such activities and life processes have changed throughout history, from basic vital resource usage (water, food, energy) to increasingly complex uses required in industrial contexts. This has changed the composition and quantities of wastewater and stormwater, as well as their recovery rate [11].

The problem addressed in this paper is not new; it has arisen and been solved throughout human history, in all civilizations and settlements. The recovery and reuse of resources have always been integral practices in rural, predominantly agricultural environments, that mainly use natural energy and matter (solar society), generating organic waste resulting from life and working processes [12]. Organic waste from the household and domestic animal breeding and farming are integrated for joint processing and use. Within this framework, everything that has been produced and used will be circulated back into reuse, spanning applications in households, animal husbandry, and diverse agricultural sectors. Historically, various dissipative processes and technologies have been tailored to specific climatic conditions and needs, including wastewater and organic matter recycling. In this manner, very little organic waste (or other types of waste) was thrown away, bolstering the sustainability of the household and the farm [12]. These systems minimize the external supply of energy, water, and food, and which is the goal of sustainable urban systems.

As more people adopt diverse professions, the traditional practice of local individual resource recovery is becoming increasingly difficult to implement, gradually becoming an urban service activity organized at the city level. Since 1900, increasingly large cities have been built that consume greater amounts of energy, water, food, and other resources, creating ever-increasing amounts of wastewater and continuously pollute the soil, air, and water, thereby reducing resource availability [13]. Therefore, resource recovery practices were gradually introduced. In recent times, the situation has been changing rapidly because needs are increasing while available resources are decreasing and are located further away; simultaneously, environmental pollution is increasing [13]. The constant daily needs for livelihoods in large cities are high (water: 150 L/inhabitant/day; energy: 12 kW/inhabitant/day; food: 1.85 kg/inhabitant/day), supply chains are increasingly complex, and the availability of natural resources is decreasing and becoming more remote; thus, the systemic vulnerability of urban areas has intensified.

At the same time, as an external pressure, climate change increasingly affects the availability of vital resources, urban infrastructure, and the safety of living and operation of UWSs. Extreme weather events (temperatures, floods, storms) create imbalance and disorder in the environment and urban areas, straining the system. This is especially evident in areas with a seasonal tourist economy, which internally reinforces the imbalance through increased seasonal demand. Thus, these urban environments and dissipative structures are particularly exposed to climatic and economic pressures that reduce their resilience and sustainability. For these reasons, the application of an IRM framework and

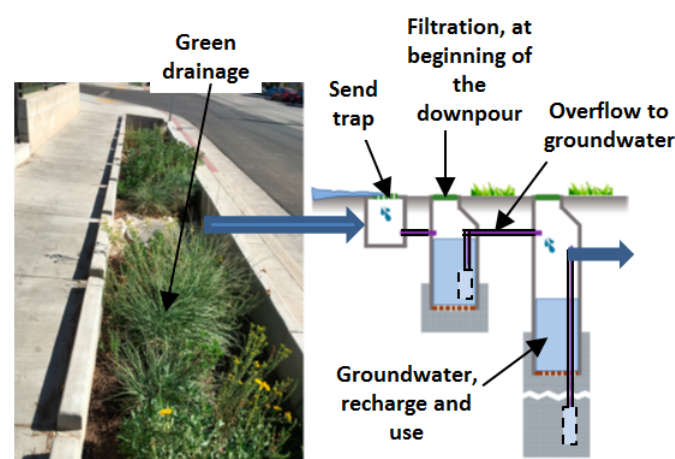
the circular economy strategy is becoming more and more important. It is necessary to organize the recovery of all available resources in a controlled and proper manner in order to prevent health and safety problems that would threaten urban livelihoods and society in general.

To accomplish this, a prerequisite is good knowledge regarding the availability and characteristics of the resources generated with UWSs. These are resources that are constantly available in the urban environment itself, and are ready for recovery with appropriate processing and treatment [14–16]. They are not directly dependent on supply chains or other supply issues, and are therefore reliable in all situations. In order to enhance sustainability, it is very important to solve the problem systematically and comprehensively, involving all stakeholders by implementing IRM across the system. It is also important to be aware that every technological application results in increased entropy. Technologies based on natural processes and energy are more open and comprehensive, facilitating the exchange of energy and matter with the environment, thus slowing increases in entropy [12]. To ensure the effective circulation of vital resources, solutions to this complex and demanding problem must be locally optimized.

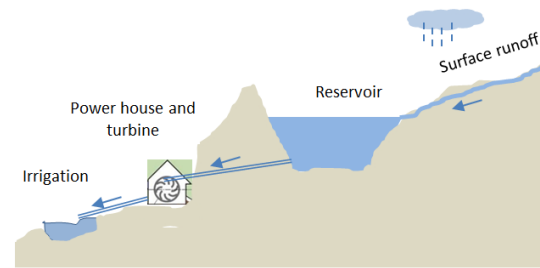
### 3. Urban Water System Resources Recovery Concepts

#### 3.1. Storm Drainage System

Urban surface runoff washes away impurities from the city's surface, leaving the waters contaminated with various substances. Pollution load is highest at the very beginning of runoff and decreases significantly over time, which affects the application of water reuse schemes. Runoff poses a threat to people, property, and the functioning of the city due to flooding. As the unpredictable input of rain and pollution produces an unpredictable output, cities attempt to regulate runoff and pollution by implementing retention measures and reservoirs, as well as sediment and oil traps. Retained water is a potential water resource for various purposes (e.g., process water, fire protection, cooling, irrigation), and even for water supply (as in Singapore) (Figure 5) [16], where the value of such water is informed by the magnitude of droughts in the considered area. In addition, retained/stored water is a possible source of hydropower, which can be integrated into water use schemes (Figure 6); in this context, the potential depends on the gravitational potential energy of the reservoir.



**Figure 5.** Elements and processes of direct and indirect rainwater recovery.



**Figure 6.** Hydro energy recovery and water use concept for urban stormwater runoff (arrows—energy and water flow).

Stormwater has been used for a long time in many countries, both developed (e.g., USA, Australia) and developing (e.g., India). The biggest obstacle to its widespread use is the lack of a regulatory framework, variability of the inflow in terms of quantity and quality, and uncertainty in water treatment efficiency, which is expected to increase due to climate change.

To address these problems, urban planners and engineers have adopted Water-Sensitive Urban Design (WSUD). This approach involves integrating stormwater infrastructure into the urban environment using green solutions (e.g., detention basins, constructed wetlands, rain gardens, permeable pavements, green roofs), as shown in Figure 5. These nature-based solutions slow water flows, reduce peak runoff, capture water, and reduce the energy/velocity of water through infiltration, evaporation, transpiration, storage, and filtering of water using directed ground flows and vegetation. Therefore, controlled infiltration of rainwater into groundwater, evapotranspiration of water into the atmosphere, and capturing and storing rainwater, as well as directing environmental water from overlying areas which would otherwise threaten the urban area are considered acceptable solutions [8,15]. These approaches can also contribute to biodiversity enhancement, urban cooling, CO<sub>2</sub> capture, increased oxygen concentrations and air quality enhancement, and overall improved landscape amenity value of urban spaces. Integral solutions for stormwater protection and use are a promising concept that is increasingly being applied in many settlements, especially those with combined drainage systems (stormwater and wastewater), as keeping stormwater outside the combined drainage system reduces uncontrolled overflow of polluted water into the sea and water resources.

The biggest management problem is the stochastic nature of the quantity, quality, and duration of runoff, including the large seasonal differences; for example, between (rainy) winter and (dry) summer. Seasonal water storages are a suitable solution, if they can be realized, which reduce peak runoff, mitigate erosion processes, and provide water for various purposes during the dry season. Water is trapped as a water flow, as occurs in natural hydrological systems, to maintain water availability and reduce entropy. Water storage is a key element affecting the sustainability and cost-effectiveness of stormwater use. The increasing climatic variability of precipitation is expected to make stormwater management more difficult, requiring both artificial and natural retention basins with increased retention capacity. The application of green/blue solutions reduces the growth of the system's entropy through the integration of environmental processes. Gray/building structures are not self-adaptive to environmental pressures and, unlike green ones, cannot adapt to climate changes without human intervention, thus having a limited lifespan and capacity. As such, green solutions significantly contribute to increasing the quality and competitiveness of a tourist destination.

### 3.2. Wastewater System

Wastewater consists of 99% water, while the remaining 1% comprises a complex mixture of contaminants; for example, organic matter (fats, food scraps, human waste), nutrients (nitrogen, phosphorus), pathogens (bacteria, viruses), inorganic solids (sand, metals), and chemicals (soaps, detergents, pharmaceuticals, pesticides) of domestic or industrial origin. Therefore, wastewater must be purified before its discharge or use. For this purpose, several treatment stages are applied, which rely on a combination of physical, chemical, and biological processes that ensure an effluent quality that meets the standards; that is, “fit-for-purpose” treatment is applied [11]. A large number of technologies can be applied, making the selection of an optimal combination a difficult task [16,17]. Wastewater treatment yields three main outputs—treated water (effluent) that is safe for discharge or reuse, sewage sludge (biosolids) that can be used for fertilizer or energy, and biogas (methane) from anaerobic digestion, which can be used to generate energy—alongside other byproducts such as heat, nutrients, and greenhouse gases, all of which are crucial for resource recovery and environmental protection.

Municipal wastewater has been used for a long time as a resource, and the associated advantages and disadvantages are well known [17]. The largest and most traditional application is the use of treated wastewater for irrigation and biogas as a renewable energy source. The organic matter from sludge is converted into a gas containing more than 60% methane via an anaerobic process. It has been reported that about 1.5 kWh/m<sup>3</sup> can be obtained from raw wastewater if the COD is between 250 and 1000 mg COD/L [17]. The produced gas can be easily stored, transported, and used as needed to produce heat and power. Extraction of thermal energy from wastewater is increasingly being practiced. The temperature of wastewater in the drainage system is between 10 and 25 °C, and thermal energy in the form of heat can be recovered from wastewater using various technologies (heat exchanger, heat pump) that are simple, proven, and environmentally friendly. The resulting thermal energy (about 5.8 kWh/m<sup>3</sup> for a 5 °C drop in wastewater temperature) can be used for the direct heating of homes and agricultural greenhouses, among other purposes. In the context of the growing energy crisis, this form of wastewater recovery is becoming increasingly cost-effective at the local level. The implementation of various recycling practices at sewerage treatment plants has become important approach to solving water and energy dilemmas, promoting green and low-carbon development.

Wastewater can also contain hydraulic potential energy if there is a height difference in the system (i.e., the pressure between the inlet and outlet), as well as the velocity head (kinetic energy). Due to the characteristics of wastewater and the fact that the system is gravity- rather than pressure-driven, its use is limited to very special situations, such as membrane energy recovery. In cases where the drainage system is located deep beneath the city for easier transport, geopotential energy may be generated (Chicago, Singapore, and other big cities) [18].

Water consumption (water supply system) directly affects the wastewater recovery capacity. Tourists use more water and produce more waste than typical residents, thus significantly increasing both the peak demand and pressures on the sewerage system and environment. This applies to energy and sludge (nutrient) production and recovery capacity, determined by number of population equivalent (PE) in tourist areas (also called the Floating Population). The pollution (BOD) load of a tourist is 20–40% higher than that of a standard resident value for PE in EU (60 g BOD/day; 5-day BOD) [9]. A similar situation occurs with water consumption, which increases significantly for the hotel/accommodation category. For this reason, the resource recovery potential (and, thus, the associated profitability) is higher than in other cities.

The reuse of treated wastewater and biomass from the sludge reduces strain on freshwater and natural resources and enhances sustainability, creating a stable, alternative water supply and therefore reducing seasonal water and energy peak demands in tourist areas, thus alleviating the stress in the resource supply chain created by seasonal tourism in coastal environments, as well as reducing the seasonal cost of water. Such a system can significantly strengthen the sustainability and increase the reliability of tourism activities, especially in regions with insufficient freshwater and natural capacity due to climate change (droughts, altered rainfall), overuse (irrigation, industry), pollution (agricultural runoff, wastewater), and poor management.

### 3.3. Water Supply System

Recovery in the water supply system refers mostly to energy recovery. Recovery can be practiced in advance where water transport conditions allow it, and as a measure to manage water losses that occur due to the variability of water consumption in the supply area, which results in pressure variability in the water supply network. Therefore, in the water supply system, considering the excess water pressure in periods of low water consumption and height differences within the water pipe system, there could be significant hydropower potential for electricity production. Excess water pressure energy is traditionally eliminated using pressure control valves and shut-off chambers, which increase energy losses and thus system entropy. Instead of eliminating it, excess pressure can be utilized by installing micro hydropower systems that do not interfere with the functioning of the water supply system. Various solutions are being applied that reduce water pressure while producing green energy, thus contribute to reduced energy loss, greenhouse gas emissions, and water losses in the system due to pressure levels [18,19]. As an internal source of energy, this contributes to the security of water supply and reduces water abstraction. In particular, high pressure regularly occurs every day during times of low water consumption; mainly at night. This phenomenon similarly affects tourist areas, where high pressure occurs in water supply pipelines throughout the entire off-season period of the year, spanning 6–8 months. It is obvious that these are large potential capacities and, for this reason, the profitability of energy utilization is viewed more broadly, taking into account all effects—not just economic and technological ones.

Water supply reservoirs can be adapted to serve as storage for hydropower production through the implementation of an urban pump–storage–hydroelectric plant system integrated with green energy sources (e.g., solar, wind, chemical), thus reducing the impacts of their intermittent production and better adapting to the needs of the UWS and urban system [20,21]. This is a concept that strengthens the energy supply sustainability of the city by managing energy supply derived from intermittent sources. In all cases where there is an excess of available reservoir volume, it can be used as energy storage; for example, as is realized through PSH plants in tourist areas [20]. Thus, the shortcomings of the seasonal water system in tourist areas can become an opportunity to strengthen sustainability, if they are adequately adapted.

If the water supply system is based on suitable (low-cost) water resources and has adequate gravitational potential energy then, in the winter rainy period when water consumption in tourist areas is very low, it can be used for green energy production as well as to supply water to other economic sectors (agriculture, water bottling industry). Highly variable water supply systems can be adapted to supply water for irrigation by implementing appropriate water reservoirs. In the rainy winter period, the off-season surplus capacity of the water supply system can be used for irrigation and to supply seasonal water reservoirs for summer water uses for various purposes as, when in season, the system does not have (surplus) capacity for these purposes. Maintaining appropriate

constant flow (use) of the water supply system in the off-season period reduces water quality deterioration due to water retention, and provides additional revenue to cover the ongoing costs of off-season maintenance and operation. This integrates the system with the local agricultural and industrial operators that supply tourist areas, ultimately strengthening the area's competitiveness.

The aforementioned integration of water supply systems with energy and food supply systems strengthens the resilience of the urban system and the security of society in adverse climatic periods and incident situations, as the supply is multiplied and diversified. Significant improvements can be achieved if all the abovementioned options are planned in advance as planned adaptation measures for climate change, considered as a proactive strategy across various infrastructures. These measures help to integrate climate resilience into development using systemic approaches.

### 3.4. Recovery Concepts

The long-term vision for achieving sustainable urban environments is to create a “total urban system” [22]. The essence of a “total urban system” is understanding the whole picture—how everything in a city and its network with other cities works together—to solve complex problems and plan for a better future. Simply put, this means treating all relevant urban systems and resources in an integrated manner, more fully networking them into a new, more comprehensive circular system to support the sustainability of citizens, the economy, and the natural environment in a climate- and resource-uncertain future. The integration and circulation of water, nutrients, and energy reduce the sensitivity and vulnerability of individual water infrastructure, urban water systems, and the urban environment as a whole, thus strengthening their resilience and reducing risks by creating appropriate feedback loops to support supply. This involves planning integrated recovery approaches to manage urban food waste, water, and energy through recovering valuable materials, nutrients, water, and energy; implementing technology (e.g., composting/recycling); and developing policy for sustainable, cost-effective outcomes. Integration enables easier and more effective adaptation to all expected and incident stresses that the future may bring. A true circular economy requires full integration across systems, businesses, and policies to function, moving beyond simply recycling to a holistic design where waste is eliminated and resources are continuously looped—for this purpose, it is necessary to connect resources, consumption, and recovery into one closed-loop system for maximum sustainability and value. Integration is not a part of the circular economy; it is the mechanism that makes it work, connecting everything from energy systems to material flows (water, food) into a cohesive, sustainable loop. In this context, key steps include waste segregation, stakeholder engagement, feasibility analysis, and designing integrated systems to recover resources (water, nutrients, energy) while balancing economic, social, and environmental goals.

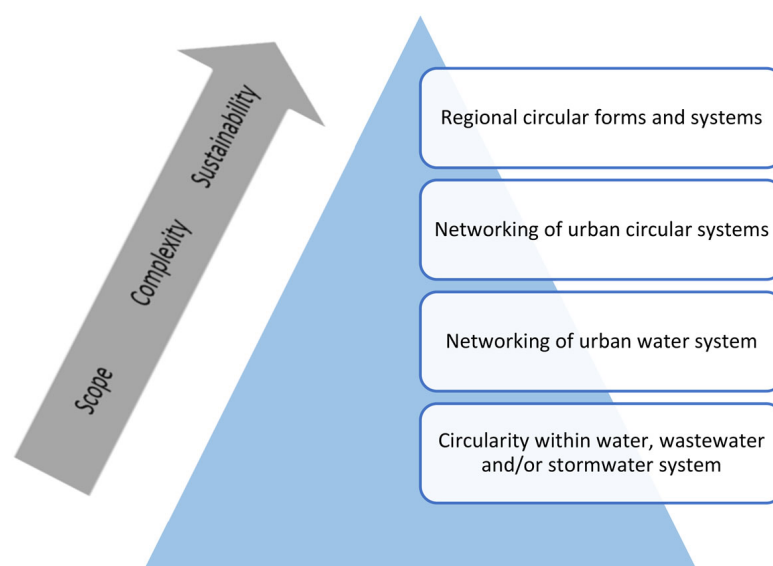
The bottom-up approach is considered an appropriate framework to explore such concepts. This means that the internal integration and circulation of resources (water, nutrients, energy) within water supply, wastewater, and stormwater systems should be first assessed separately. This is the *zero level* of resource recovery concepts; which, in certain environments, is the beginning of the application of CE strategies. At this stage, assessments and data collection are carried out, considering water usage, energy demand, nutrient (N, P, K) flows, and so on. Then, possible paths and procedures for more complete resource recovery (e.g., of water, nutrients, and energy) in the UWS as a whole are considered. This concept is the *first level* of the integrated resource recovery process, in which UWS resources are considered together, not in silos. Key roles are given to specialists, such as engineers specialized in the planning, designing, and building of UWSs, in accordance with

professional rules and practices. Relevant city departments, spatial planners, and other professionals should always be consulted, as should the public and other stakeholders. Successful implementation of the CE at the first level is a prerequisite for higher and broader integration within the urban environment and the natural environment.

The *second level* of integration refers to the network of waste, water, and energy circulation (feedback) processes between urban waste (segregated organic waste), water, and energy systems, among others. At this level, specialists in the management and development of urban infrastructure that function as interdependent recovery systems in urban areas play a major role. Specialists and relevant stakeholders in their area of expertise are consulted as needed, all interacting to capture a city's dynamic environment and performance, from resource flows and circulation to social cohesion.

The *third level* concepts encompass urban and regional forms and systems, where the urban form denotes what a city looks like, regional form denotes how cities and land fit together, and planning refers the actions intended to shape the future of both. Forms describe the physical patterns, structures, and land uses of cities (urban) versus broader areas, focusing on their density, infrastructure, circular economy schemes, and settlement types, which are managed through planning to balance growth, sustainability, economic needs, and quality of life across scales from neighborhoods to entire regions. Understanding these forms and systems helps planners to manage challenges such as climate change, infrastructure congestion, pollution, housing and resource shortages, and economic disparities, fostering more sustainable, equitable, and efficient urban environments considering circular economy implementation as a strategy within integrated resource management frameworks.

A proposed circulation concept integrates pollution reduction and carbon mitigation, resource recycling, and energy synergy. Cyclic approaches make sense, as they ensure both the dynamic stability and autonomy of urban water and other systems, as well as enabling activities to be linked together to enhance the transfer of water, energy, and other resources directly to those requiring them. Closing cycles and linking them up yields pathways that readily reverse the direction of urban resource flows, thus improving the resilience and sustainability of urban systems. Developments from levels zero to three for the coupling/integration of circular systems in coastal urban areas contribute to resource self-sufficiency, thus promoting the achievement of green and low-carbon objectives (Figure 7).



**Figure 7.** Hierarchical structure of circular concepts development.

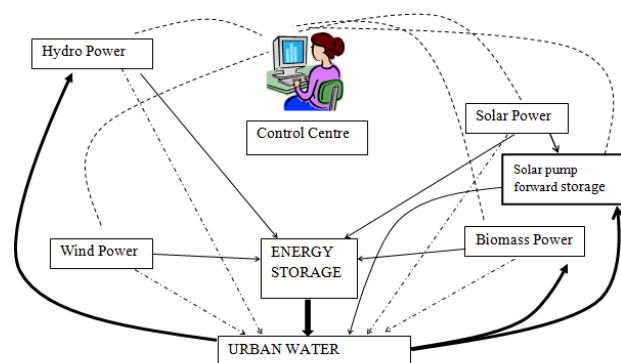
In this context, emphasis is generally placed on technological innovation; that is, on less-dissipative circular coupling concepts and structures. Such concepts provide long-term stable and reliable water, energy, and nutrient supplies. The sustainability of the system is assessed based on the tendency to maximize non-dissipative circular flows of water, matter, and energy while minimizing dissipative flows. Diagnostic criteria are utilized to evaluate a circular system's ability to minimize waste and maintain resource value through closed-loop processes. Sustainability can be achieved through optimizing the storage capacity; the number of cycles in the system; the efficiency of resources use; spatio-temporal differentiation, which translates into diversity of users; the balance between flows of energy, water, and other resources; and the reciprocal coupling of processes [6]. This can be expected to improve resource efficiency and flows, the percentage of waste re-entering new cycles of use, and the mitigation of environmental impacts, thus reducing entropy production in urban water systems, urban systems, and natural systems.

The systemic planning of urban adaptation is conducted with the aim of achieving the complete integration of resources through the implementation of a rational and reliable circular economy. The effectiveness and sustainability of circular economy implementation increase along with the stage of bottom-up implementation, as well as the system's complexity (see Figure 7). This is expected, as the unknowns surrounding the application, processes, and consequences are most recognizable locally. With wider networking, the complexity, unknowns, suspicion, and decision-making risk all increase, which is expected due to the increased number of multidisciplinary subjects and actors, serving as stakeholders. Consequently, the assessment methodology and decision-making process grow in complexity and uncertainty due to the large number of data and actors. The first steps in CE implementation need to be taken at the local level, in accordance with local needs, locally available data and knowledge, and acceptable technologies.

The selection of a systematic recycling and reuse concept is crucial in the development of a circular system. Potential solutions are defined, evaluated, and a specific configuration is chosen for detailed engineering assessment. The following topics are considered: (i) *Economics and value chain*—Processing costs, resource quantity, resource quality, market value and competitiveness, use and application, distribution and transport; (ii) *Environment and health*—Emissions, health risks; (iii) *Society and politics*: Acceptance and support, policy and regulations.

In environments where there is a periodic or permanent shortage of water, food, and/or energy, there is no alternative to recycling, and the recovery and reuse of urban resources has a significant impact on reducing the entropy of the city and the environment.

The complete and reliable supply of UWS with renewable resources requires the implementation of a local smart grid for a specific resource or group of resources (Figure 8). The network should integrate all or some of the local urban resources—for example, solar-based green energy—to achieve a secure (and preferably complete supply) of electricity for the UWS. One of the characteristics of such a system is redundancy, denoting that the UWS has more than one way to obtain energy; this would be a significant step towards a sustainable supply of energy. Additionally, as the UWS is essentially the bloodstream of every settlement, this would be a significant step towards sustainable living in urban communities. However, a smart grid integrating advanced technologies must also be implemented, enabling the integration of renewable and distribution systems, real-time visualization and control, and energy storage and power electronics [21]. It is expected that the future sustainability of cities will be based on similar solutions [23].



**Figure 8.** Smart grid network for integrated renewable energy management (bold solid arrows—resources from UWS; solid thin arrows—energy towards energy storage; dashed arrows—information; dotted arrows—renewable energy to UWS).

## 4. Discussion

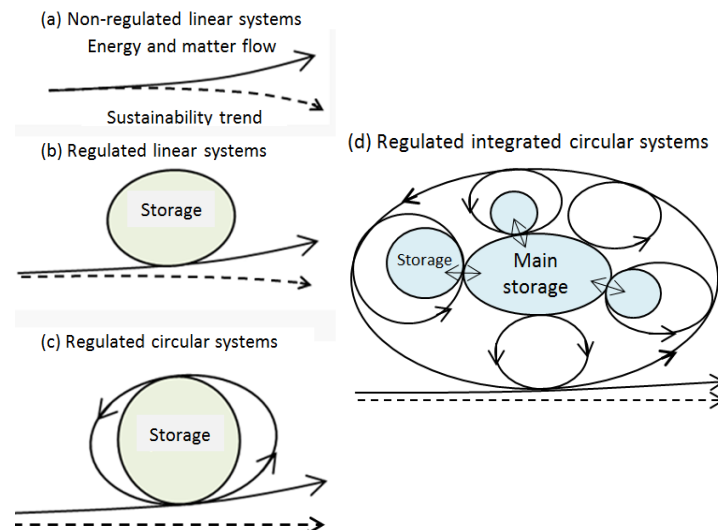
The benefits of a sustainable circular economy (SCE) for tourist areas include enhanced provisioning (e.g., of energy, food, water) and local climate regulation, supporting nutrient cycles, cultural services, and recreation. The SCE ensures a stock and flow of tangible resources (energy, water, and nutrients), landscape, and living components (ecosystems). Although SCEs are difficult to quantify monetarily, valuing recovery capital helps to raise awareness and inform policy, especially considering the relative costs of linear UWSs.

### 4.1. Theoretical Foundation for Understanding Circulation in Urban Water Systems

The standard UWS is a linear open-loop system with high resource input and waste output (Figure 9a,b). The water supply and sewerage systems are treated as interconnected linear systems that follow a “take–purify–supply–collect–treat–dispose” model, extracting natural resources, creating water supply and wastewater services, and discarding collected wastewater as effluent into water resources. Its short-term design objective is urban water supply and consumption, followed by collection, treatment, and disposal of the used water. The outcome of this system is waste, pollution, reliance on new water resources, high sensitivity and vulnerability, and low adaptation capacity to external and internal stressors. Stormwater systems are also linear open-loop systems that follow a “collect–drain–treat–dispose” model, protecting urban area from flooding by discharging collected runoff water into local resources, leading to the depletion of local water resources capacity while increasing water pollution. As a linear open-loop stochastic flow system, it reduces the sustainability of the local natural and human environments, as urbanization and stormwater systems disconnect urban runoff from local hydrological cycles. Linear UWSs involve storage/reservoir systems to manage demand/outflow regulation to users, characterized as a particular approach applied to simplify complex natural inputs into a manageable system to predict output behaviors over time (Figure 9b).

In contrast, circular UWSs aim for closed-loop cycles, conserving resources and cutting pollution (Figure 9c). The circular UWS shifts to a “reduce–reuse–recycle” model, designed for long-term services to keep water, nutrients, and energy in use, thus minimizing waste and fostering sustainability. It is a closed-loop system that keeps resources in use but remains open for additional resource supplies, thus minimizing resource degradation. The goal of such a system is the provision of long-term services, resource efficiency, and waste minimization/elimination. Key outcomes include a reduction in virgin resource inputs and emission outputs, lower cost, and new service models that enhance resource and services security through reducing system sensitivity and vulnerability, increasing the adaptive capacity to external and internal stresses, and fostering sustainability. Storage is a crucial element in a circular UWS. Storage in a closed-loop cycle involves systems where

water, materials, or energy are continuously circulated, reused, or recycled, creating a self-contained system that minimizes waste and external inputs, as seen in natural systems to support the circularity of energy and matter, contrasting with open systems that deplete resources (Figure 9c). In a circular system, storage reduces that observed in a linear system but does not necessarily replace it; for example, in a water supply system.



**Figure 9.** Schematic representation of characteristic systems, entropy growth, and weakening of sustainability (solid arrows—energy and matter flow; dashed arrows—system sustainability trend). (a) Non-regulated linear systems. (b) Regulated linear systems. (c) Regulated circular systems. (d) Regulated integrated circular systems.

An integrated urban circulation system include centralized multi-service storage because it services multiple circulation systems—not just one type of infrastructure and its storage (Figure 9d). As such, the storage system moves from single infrastructure management to active management within an urban system designed to keep resources in use for as long as possible, reducing environmental impacts and creating new economic value. In this system, centralized storage with multiple inflows and outflows is implemented, focusing on efficient water/gas/matter handling within the urban system. Such storage is an element on which the sustainability of circulation systems depends, as in nature; therefore, storage is an inevitable element for strengthening the sustainability of urban systems.

The formulation for storage with multiple inflows and outflows relies on the continuity equation, defined as  $\text{Inflow} - \text{Outflow} = \text{Change in Storage } (\Delta S/\Delta t)$ . The core principles is a mass/energy balance  $\Delta S/\Delta t = \sum I - \sum O$ , where  $S$  is the storage volume,  $I$  denotes all inflow rates,  $O$  denotes all outflow rates, and  $\Delta t$  is the time step.

Therefore, linear systems focus on throughput that creates waste, while circular systems focus on prevention of waste and maximization of resource values by design; therefore, it seems that linear systems are fated for obsolescence, as circular systems foster much more resilient services. As a result, linear systems are environmentally harmful, while circular systems are environmentally friendly. It is obvious that circular systems reduce sensitivity and vulnerability while strengthening the resilience of tourist areas and their activities, both in relation to climate change and to internal threats arising from extremely high variability in resource use. SCEs can mitigate the unsteady flow of resources (both in the system and environment), the seasonal nature of economic activities, and the resulting consequences on urban metabolism and consumption of resources that have significant impacts on the operation and sustainability of UWSs and other urban infrastructure, financial resources (public/private), and essential physical/social systems (food, energy).

Input–output thermodynamics provides a framework to track energy and matter transformations, ensuring that “what goes in must come out” in some form; even if it is less useful than intended. In essence, input–output thermodynamics provides the accounting framework (mass/energy balances) to analyze how physical systems such as dissipative structures (as in the case of UWSs) transform inputs into desired outputs within certain boundaries, respecting fundamental conservation laws.

The Second Law of Thermodynamics states that every process increases disorder (entropy); this means that reuse and recovery cannot be 100% efficient, as material/water quality degrades, requiring energy and water inputs and generating waste/entropy, thus making perfect resource and material loops impossible. The efficiency of the system (Useful Output/Total Input) defines its entropy. In a one-way input–output UWS, entropy is therefore significant and can be slowed down by reducing the total input (abstraction of water) and increasing the useful output (recovered resources). In order to reduce the peak abstraction of water, reservoirs are utilized to regulate the input–output process (Figure 9b), with the goal of reducing maximal abstraction ( $Q_{\max}$ , supply,  $\text{m}^3/\text{s}$ ) by bringing reuse closer to the average demand value ( $Q_{\text{ave}}$ , demand,  $\text{m}^3/\text{s}$ ).

For this reason, management models for achieving sustainability of water supply are inherently one-way, implying minimization of losses ( $V_{\text{loss}}$ ,  $\text{m}^3$ ) while reducing the total water abstraction ( $V_{\text{in}}$ ,  $\text{m}^3$ ) and peak supply capacity ( $Q_{\text{in}}$ ,  $\text{m}^3/\text{s}$ ), considered in relation to all resources necessary for the operation of the system (energy, matter, capital). Sewerage system management models are also simple, focusing on minimizing losses/uncontrolled leaks ( $V_{\text{loss}}$ ; reflecting environmental pollution) and improving the installed capacity of structures/system elements ( $Q_{\max}$ ) in order to reduce the consumption of energy and materials. The same applies to stormwater systems, which aim to minimize flooding damage and improve the installed capacity of the drainage structure ( $Q_{\max}$ ). To achieve this, it is necessary to develop natural storage systems (lakes, wetland, aquifers, and rivers) and man-made reservoirs that capture, store, and release stormwater to achieve sustainable flood mitigation, water use, and ecological health.

Appropriate mass balance estimation primarily considers virgin inputs, the water in the water supply system, used water in the wastewater system, rainfall in the stormwater system, and waste and discharge as outputs. In a one-way input–output UWS, entropy is therefore significant and can be slowed down by reducing the total and peak inputs through implementing service reservoirs and increasing the useful output. This strategy has long been practiced to strengthen the sustainability of UWSs. Peak runoff in urban stormwater system is regulated in a similar way, through the implementation of retention basins/reservoirs. These are all actions that strengthen the sustainability of the UWS, mitigate shocks/variabilities, and strengthen resource allocation.

Processes that generate, consume, and accumulate resources take place in circular systems, making the mass balance more complex. In particular, the mass balance in a circular system tracks the input of virgin resources ( $V_{\text{in}}$ ) mixed with recovered ( $V_{\text{recovery}}$ ) and/or reused ( $V_{\text{reuse}}$ ) resources (i.e.,  $V_{\text{gen}} = V_{\text{recovery}} + V_{\text{reuse}}$  for supply), and waste resources ( $V_{\text{out}}$ ), resources accumulated ( $V_{\text{accum}}$ ), and lost resources ( $V_{\text{con}}$ ) as output. Therefore, it can be summarized as follows:

$$V_{\text{accum}} = (V_{\text{in}} + V_{\text{recovery}} + V_{\text{reuse}}) - (V_{\text{out}} + V_{\text{con}})$$

The key difference in mass balance determination between these systems is the mixing feedback flow of resources ( $V_{\text{recovery}} + V_{\text{reuse}}$ ) and resources used in production processes ( $V_{\text{con}} + V_{\text{accum}}$ ). In addition, resource recovery requires the application of reservoirs/storage to ensure sustainable circulation (Figure 9c). It follows that the increase in

Vout + Vcon causes and increase in entropy, while an increase in Vacuum improves resistance and sustainability.

In a circular model, mass (energy) balance determination helps to manage the transition by tracking recovery or/and reuse water, energy, and matter mixed with virgin resources. This allows companies to claim a certain percentage of recycled content in the final production of resources (water, energy, and matter), showing progress towards circularity and reduced use of virgin resources, effectively closing the loop on water, energy, and matter flows. It goes without saying that greater resource recovery strengthens the sustainability of a UWS. Such systems are less sensitive and vulnerable to external and internal variabilities, as they allow for adaptive planning and management. Success is defined in terms of the quantity and quality of the accumulated resources (water, energy, nutrients). CUWS designs reduce waste, keeps materials in use via reuse and recovery, and helps to regenerate nature, creating a closed system with minimal virgin resource inputs and waste outputs, using methods such as mass balance to track the recovered resources.

The key difference in mass balance between a linear UWS and a CUWS is the flow: a traditional linear system is a one-way street to environmental and landfill waste, while a circular system aims to perpetually cycle resources, using techniques such as mass balance to allocate recycled outputs as inputs to specific services. The core difference is “where” matter and energy are used: linear systems burn and utilize significant amounts in primary resource processing and supply, whereas circular systems shift water, matter, and energy to maintain loops (reuse, recovery), leading to a much lower net demand by avoiding the most matter- and energy-intensive initial steps, as well as mitigating high seasonal demands. For these reasons, CUWS are energetically and materially efficient and environmentally sound, making them especially relevant for tourist areas that rely on sustainable implementations to support frameworks for *sustainable destination programs* [11,24,25].

#### 4.2. Framework for Future Research

The solution lies in the application of *sustainable design*, which aims to move away from linear “unsustainable” flows toward circular systems that reduce inherent entropy. Key approaches include Life Cycle Assessment (LCA), System Dynamics, and integrating data with the UN Sustainable Development Goals for the exploration of concepts and scenarios. Actions such as wastewater treatment and water distribution inherently produce entropy. Therefore, reusing treated wastewater, biogas, and heat originating from treatment plants can significantly decrease the overall entropy budget of the system, reduce carbon emissions, and improve sustainability. Information entropy concepts are also used to assess the complexity and order of urban ecosystems, including water systems, helping to gauge developmental levels and harmony. High entropy means high randomness in data (high unpredictability), while low entropy means low randomness. For example, the water demand in tourist areas has significantly greater unpredictability as the tourism economy is very sensitive to external and internal stresses, which increases randomness and risk for both the tourism economy and the natural environment.

UWSs are open, dissipative systems that naturally increase entropy (losses, disorder) as water moves through them. Designing for non- or less-dissipative flows means making the system more organized, creating more uniform flows, and minimizing energy dissipation, water losses, and pollution (minimizing entropy) through CE implementations via creating CUWSs. In order to achieve this, it is necessary to apply system analysis using entropy budgets (entropy production + entropy exchange) to quantify losses and assess the impacts of feedback loops in terms of water, energy, and nutrient recovery and use. In addition, it is necessary to apply *sustainability modeling* employing entropy concepts to guide urban planning towards circularity and reduced environmental impacts. Notably,

lifecycle thinking, resource efficiency, and circular economy principles should be integral aspects of these modeling and storage design approaches.

The urban wastewater recovery system contributes significantly to the sustainability of the urban system in tourist areas, complementing and strengthening the local water–food–energy nexus [10,13,26]. These systems transform sewage into valuable resources including clean water, energy (heat/biogas), and nutrients (phosphorus/nitrogen) via appropriate treatment technology, and are easy to integrate with food waste systems. All resources can be used immediately locally, so the required storage capacity is low. Their application in tourist areas has a significant impact on the sustainability of both the economy and society. Therefore, it is necessary to further promote technological innovation, including sewage-to-quality reclaimed water transformation, sludge-to-energy transformation, exhaust gas treatment technology, and urban resource system integrations. Tourist coastal areas are a specific environment that require appropriate sustainable solutions.

The stormwater system contributes to the recovery of water and energy, mostly in the winter rain period [15,27]. It is a complex and demanding system to manage due to its periodic operation and stochastic input. Such systems can follow the principles of Sustainable Drainage Systems adapted to coastal karst environments and climate hazards associated with the air, land, water, and sea [28]. Due to the great variability in rainfall and temperature, each use of water requires some form of reservoir that supports reliable resource recovery. This may present a risk if not designed correctly, requiring integrated coastal area planning.

The water supply system allows for energy recovery mostly in periods of low water demand (e.g., winter), when the pressure and excess capacity in the system are highest. Urban water supply recovery systems are innovative approaches for resilient, sustainable urban water management by integrating decentralized sources such as greywater/rainwater, advanced wastewater treatment (water reclamation), smart infrastructure to reduce water and energy losses (pipe hydro-electric turbines), diversified supply inputs, and the reuse of treated water for non-potable (or even potable) needs, moving beyond traditional “take–make–waste” models to ensure water security amidst climate change and urban growth. The optimization of water supply systems with pronounced seasonal and daily variability is a problem that can only be successfully solved by exchanging water and energy resources with the internal (urban) and external natural environment, which are dynamic and insufficiently known.

These systems offer a paradigm shift, making UWSs more adaptive, efficient, and sustainable under future challenges [24]. Networking feedback loops (water, energy, nutrients) and their storages, within both CUWSs and circular urban systems, strengthen the effectiveness, resilience, and security of resource recovery (Figure 9d) [29,30]. Integrated resource management is a key framework for managing waste, water, and energy in tourist areas, enabling the reuse of valuable materials, nutrients, and energy, facilitating environmental recovery, improved economic value, and sustainable development. The wider and deeper the integration networking, the greater the safety and benefits for the environment and society. *Feedback loops and stock creation under water, matter, and energy flows are the core of the urban circulation system.* In this context, established theories and conceptual models guide analyses by structuring, defining, and focusing studies.

The application of CE principles in tourist areas is challenging due to the application of specific technologies consistent with seasonal loads and operations. Therefore, the design of storage is both important and complex. This problem involves a very dynamic time series of inputs and outputs, which differ from those in non-tourist cities due to a specific seasonal cycle related to the climate, which consists of both seasonal and off-season circular loops that differ in volume, required quality, and variability. Off-season loops are generated by the

local traditional culture of using water infrastructure, while the seasonal loop is generated by the international (mixed) culture of using water infrastructure. Winter use is relatively predictable, while that in summer is much less predictable due to the dynamic mixed culture created by tourists. In these situations, the infrastructure—especially storage—must be well planned and optimized. The key issue in relation to resource recovery and reuse is the choice of technology and the design period. The rule is that, in the case of greater internal (demand) and external supply (climate) variability, it is necessary to apply robust technology and a longer balancing period, which must also take into account the lifetime of the infrastructure (design period) and the fact that the implementation of the solution must be carried out in stages in order to better adapt to changes. These are peculiarities of tourist regions and cities that significantly influence the application of circular economy principles.

It can be concluded that the sustainability of a circular system in tourist areas is not guaranteed by itself; as such, it must be carefully and comprehensively planned and implemented [31]. The technological viability of a CUWS can be objectively assessed according to the First and Second Laws of Thermodynamics. The laws of thermodynamics—especially the first (energy conservation) and second (increasing entropy/disorder)—set fundamental limits and guide principles for technological sustainability, revealing that all transformations create waste heat and increase universal disorder, necessitating closed-loop systems, reliance on external solar energy (as in nature), efficient resource use (exergy), and a shift from linear consumption to circular economies to sustainably operate within the Earth's physical boundaries.

The ranking of possible options is a process that boils down to appreciation of the entropy of the system, constructing composite indicators or using modern technology to obtain better data, thorough consideration of energy and water management practices, and implementing sustainable operations, ultimately driving environmental, social, and governance goals and a CE [32]. However, technological assessments, in the context of sustainability, represent systematic, evidence-based processes involving evaluation of the potential environmental, social, and economic consequences of a technology throughout its lifecycle through multi-objective decision making [33,34]. Socio-economic sustainability evaluations assess how the development of a CUWS impacts people's lives, communities, and economies, balancing social well-being (health, culture, equity) with economic vitality (jobs, income) while considering environmental limits, using indicators such as income, education, health, and community engagement to identify positive/negative effects and guide mitigation for balanced, long-term prosperity.

## 5. Conclusions

This study delivers a conceptual framework that organizes ideas, theories, and variables to study concepts relevant to the application of circular economy principles to urban water systems in coastal tourist areas. It provides a logical structure to understanding the complex system of circularity involving urban water, nutrient, and energy resources in ecologically and economically sensitive areas. Such an approach allows one to freely explore ideas and concepts without worrying about the outcome, thus bringing new insights by asking questions beyond the scope of surveys and traditional methods. It allows for the use of complex models such as dissipative structures, sustainability, and circular thermodynamics, leveraging existing theories with respect to specific study goals; furthermore, critical analyses can be performed without having to go through all the steps of a traditional survey. Conceptual research helps to reach a goal/objective/better than other types of research methods based on empirical or experimental data, as such studies help to organize complex problems into understandable components, thus building knowledge.

Therefore, conceptual research very relevant as part of pre-investment studies supporting investment decisions under growing external (climate) and internal (economic) variability.

However, conceptual studies may reflect all the relevant knowledge and existing information (literature, theories), although difficulties with data collection can be mitigated if sufficient financial resources are available. Such studies are based on a low level of participation, as conceptual research involves creating new knowledge and concepts through thoughtful analysis (knowledge), rather than empirical measurements. Through clarifying concepts, it provides a basis for stakeholder selection and participation, as well as more rigorous analyses to support investment decisions.

The sustainability of circular systems is not necessarily guaranteed, generally requiring careful and comprehensive planning and implementation. Therefore, it is necessary to study the technological viability of possible circular concepts and assess their socio-economic sustainability considering aspects such as the technological framework, economic and value chains, environmental and health issues, and social and policy frameworks. Storage is a crucial element of circular urban water systems, enabling the extended use of resources effectively keeping them in the loops to reduce the demand for virgin resources and production of waste. They act as vital infrastructure for managing inflow and outflow processes, ensuring the reliable supply of resources. By moving storage from a linear concept to a dynamic circular one, circular systems reduce the dependence on new resources and encourage sustainable consumption. Storage must be optimized in relation to purpose, capacity, physical layout, and potential energy, and the storage of resources such as water, gas, and solid or semi-solid matter should be integrated into an easily manageable and reliable operation system across the entire supply area. How to optimize such a system under an increasingly uncertain and unpredictable environment threatened by climate change and rising mean sea levels—as is often the case for tourist areas—is a topic that needs to be further explored.

This study demonstrated that, in order to strengthen the tourism economy and environment in the coastal area of Croatia, it is necessary to implement circular urban systems integrated with other resource-friendly urban systems, as these karst areas traditionally lack reliable water, food, and energy resources. Importing new resources into such an environment brings about major environmental changes that can degrade the existing local conditions. Therefore, it is necessary to reduce the dependence on imports by strengthening circulation systems; that is, by keeping water, energy, and substance resources within the system itself to the greatest extent possible. The strain on infrastructure, utilities, water supply, and wastewater during peak season increases pressure on local resources, potentially leading to negative social and economic effects. This leads to low return on investment during the off-season period, while the inefficient use of infrastructure weakens the effectiveness and durability of urban water systems. The proposed frameworks and interpretations can improve the effectiveness and durability of these systems, reduce dependence on resource imports, and strengthen the resilience of the environment, economy, and society in a climate-uncertain environment.

**Funding:** This research received no external funding.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

**Conflicts of Interest:** The author declares no conflicts of interest.

## Abbreviations

The following abbreviations are used in this manuscript:

|      |                                             |
|------|---------------------------------------------|
| UWS  | Urban water system                          |
| CE   | Circular economy                            |
| IRM  | Integrated resources management             |
| US   | Urban system                                |
| CUWS | Circular urban water system                 |
| CUS  | Circular urban system                       |
| DS   | Dissipative structure                       |
| SCE  | Sustainable circular economy                |
| IVA  | Integrated climate vulnerability assessment |

## References

1. UN: United Nation's 2030 Agenda for Sustainable Development. Available online: [https://en.wikipedia.org/wiki/Sustainable\\_Development\\_Goals](https://en.wikipedia.org/wiki/Sustainable_Development_Goals) (accessed on 1 February 2025).
2. Kuzmanovic, J. Croatia's Tourism May Be Hurt by Price Hikes, ECB's Vujcic Says. *Bloomberg News*, 1 January 2025; Retrieved 2 July 2025.
3. Margeta, J.; Baučić, M.; Vilibić, I.; Jakl, Z.; Petrić, L.; Mandić, A.; Grgić, A.; Bartulović, H.; Popić, N.; Marasović, K.; et al. Interreg Mediterranean CO-EVOLVE. Elaboration of the Management Plan for the Coastal Area of the City of Kaštela 2018–2019. Management Plan for the Coastal Area. Available online: <https://kastela.hr/Portals/0/EasyDNNNewsDocuments/5443/Plan%20upravljanja%20obalnim%20podru%C4%8Djem%20Grada%20Ka%C5%A1tela.pdf> (accessed on 12 June 2025).
4. Delgado, A.; Diego, J.R.; Carlo, A.A.; Midori, M. *Water in Circular Economy and Resilience (WICER)*; World Bank: Washington, DC, USA, 2021.
5. Arab Centre for the Studies of Arid Zones and Dry Lands (ACSAD); GIZ (Deutsche Gesellschaft für Internationale Zusammenarbeit); United Nations Economic and Social Commission for Western Asia (ESCWA). Training Manual on the Integrated Vulnerability Assessment Methodology. In *Adaptation to Climate Change in the Water Sector in the MENA Region (ACCWaM) Programme*; RICCAR Training Manual, Beirut, E/ESCWA/SDPD/2017/RICCAR/Manual; United Nations Economic and Social Commission for Western Asia (ESCWA): Beirut, Lebanon, 2017.
6. Ho, M.-W. Circular Thermodynamics of Organisms and Sustainable Systems. *Systems* **2013**, *1*, 30–49. [CrossRef]
7. Mohammadkhani, M.; Masnavi, M.R.; Rezaei Hariri, M.T.; Mirmoghtadaee, M. Integrated Urban Water Management (IUWM) Framework Codification in Architectural and Urban Design: The Case of Hashtgerd, Young Cities Project. *Space Ontol. Int. J.* **2020**, *9*, 29–41. [CrossRef]
8. Margeta, J. *Stormwater and Wastewater: Pollution Load, Protection Measures*; University of Split, Faculty of Civil Engineering and Architecture: Split, Croatia, 2007. (In Croatian)
9. Margeta, J. *Sewerage of Settlements; Drainage and Disposal of Wastewater and Stormwater*; Sveučilište u Splitu, Građevinsko-Arhitektonski Fakultet: Split, Croatia, 2009. (In Croatian)
10. Feng, C.; Uber, G.J.; Palycarpou, P.P. Input-Output Model of Water Quality in Water Distribution Systems. In Proceedings of the Joint Conference on Water Resource Engineering and Water Resources Planning and Management, Minneapolis, MN, USA, 30 July–2 August 2000. [CrossRef]
11. Ghimire, U.; Sarpong, G.; Gude, V.G. Transitioning Wastewater Treatment Plants toward Circular Economy and Energy Sustainability. *ACS Omega* **2021**, *6*, 11794–11803. [CrossRef] [PubMed]
12. Almenar, J.B.; Elliot, T.; Rugani, B.; Philippe, B.; Gutierrez, T.N.; Sonnemann, G.; Geneletti, D. Nexus between nature-based solutions, ecosystem services, and urban challenges. *Land Use Policy* **2021**, *100*, 104898. [CrossRef]
13. Water Europa, Technology and Innovation, Towards a Zero-Pollution Strategy for Contaminates of Emerging Concern in Urban Water Cycle. Available online: [https://watereurope.eu/wp-content/uploads/2023/12/White-Paper-Zero-Pollution\\_online.pdf](https://watereurope.eu/wp-content/uploads/2023/12/White-Paper-Zero-Pollution_online.pdf) (accessed on 15 May 2025).
14. Abbasi, T.; Tauseef, S.; Abbasi, S.A. Anaerobic digestion for global warming control and energy generation—An overview. *Renew. Sustain. Energy Rev.* **2012**, *16*, 3228–3242. [CrossRef]
15. Luthy, G.L.; Sharvelle, S.; Dillon, P. Urban Stormwater to Enhance Water Supply. *Environ. Sci. Technol.* **2019**, *53*, 5534–5542. [CrossRef] [PubMed]
16. Zan, F.; Iqbal, A.; Lu, X.; Wu, X.; Chen, G. 'Food waste-Wastewater-Energy/Resource' Nexus: Integrating food waste management with wastewater treatment towards urban sustainability. *Water Res.* **2020**, *211*, 118089. [CrossRef] [PubMed]
17. European Investment Bank. *Wastewater as a Resource*; European Investment Bank: Luxembourg, 2022. [CrossRef]

18. ESHA-European Small Hydropower Association. *Energy Recovery in Existing Infrastructure with Small Hydropower Plants: Multipurpose Schemes-Overview and Examples*; ESHA: Brussels, Belgium, 2010.
19. Kucukaly, S. Water supply lines as a source of small hydropower in Turkey: A Case study in Edremit. In *Proceedings of the World Renewable Energy Congress*, Stockholm, Sweden, 21–25 August 2011.
20. Margeta, J.; Durin, B. Innovative approach for achieving of sustainable urban water supply system by using of solar photovoltaic energy. *Ing. Investig.* **2017**, *37*, 58–67. [\[CrossRef\]](#)
21. Margate, J. A framework for application of renewable energy in urban water systems. *Electron. J. Fac. Civ. Eng. Osijek-e-GFOS* **2018**, *9*, 1–10. [\[CrossRef\]](#)
22. O'Connor, T.; Rodrigo, D.; Cannan, A. Total Water Management, the New Paradigm for Urban Water Systems. In *EWRI/ASCE World Environmental & Water Resources Congress 2010, Challenges of Change*, Providence, RI, USA, 16–20 May 2010; American Society of Civil Engineers (ASCE): Providence, RI, USA, 2010.
23. Williams, J. Circular cities: Challenges to implementing looping actions. *Sustainability* **2019**, *11*, 423. [\[CrossRef\]](#)
24. Panganiban, E.B.; Padre, R.J.; Baguio, M.A.; Francisco, O.B.; Balderama, O.F. An Urban Water Infrastructure Management System Design with Storm Water Intervention for Smart Cities. *Int. J. Adv. Comput. Sci. Appl.* **2022**, *13*, 306–313. [\[CrossRef\]](#)
25. Tsatsou, A.; Frantzeskaki, N.; Malamis, S. Nature-based solutions for circular urban water systems: A scoping literature review and a proposal for urban design and planning. *J. Clean. Prod.* **2023**, *394*, 136325. [\[CrossRef\]](#)
26. Mulier, M.H.; van de Ven, F.; Kirshen, P. Circularity in the Urban Water-Energy-Nutrients-Food nexus. *Energy Nexus* **2022**, *7*, 100081. [\[CrossRef\]](#)
27. Dezfooli, D.; Bolson, J.; Arabi, M.; Sukop, M.C.; Wiersema, I.; Millonig, S. A Qualitative Approach to Understand Transitions toward One Water in Urban Areas across North America. *Water* **2023**, *15*, 2499. [\[CrossRef\]](#)
28. Kisser, J.; Wirth, M.; De Gussem, B.; Van Eekert, M.; Zeeman, G.; Schoenborn, A.; Vinnerås, B.; Finger, D.C.; Repinc, S.K.; Bulc, T.G.; et al. A review of nature-based solutions for resource recovery in cities. *Blue-Green Syst.* **2020**, *2*, 138–172. [\[CrossRef\]](#)
29. European Commission. *Roadmap to a Resource Efficient Europe* Brussels; COM(2011) 571 final; European Commission: Brussels, Belgium, 2011.
30. European Commission. *A New Circular Economy Action Plan. For a Cleaner and More Competitive Europe*; COM (2020) 98 final; European Commission: Brussels, Belgium, 2020. Available online: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2020%3A98%3AFIN> (accessed on 11 March 2020).
31. Newell, P.J.; Ramaswami, A. Urban food–energy–water systems: Past, current, and future research trajectories. *Environ. Res. Lett.* **2020**, *15*, 050201. [\[CrossRef\]](#)
32. OECD. *Handbook on Constructing Composite Indicators; Methodology and User Guide*; OECD: Paris, France, 2008. Available online: <https://www.oecd.org/sdd/42495745.pdf> (accessed on 15 March 2025).
33. Margate, J. Assessing the sustainability of using wastewater systems for food waste management, (Procjena održivosti korištenja kanalizacije za upravljanje otpadom hrane). *Hrvat. Vode* **2021**, *29*, 23–32.
34. Erceg, O.; Margeta, J. Selection of food waste management option by PROMETHEE method. *Electron. J. Fac. Civ. Eng. Osijek-e-GFOS* **2019**, *19*, 87–97. [\[CrossRef\]](#)

**Disclaimer/Publisher’s Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.