water

Editorial

New Advances in Rainwater Harvesting and Treatment

Anita Raimondi [1,*], Ruth Quinn [2], Ilaria Gnecco [3] and Avi Ostfeld [4]

1 Department of Civil and Environmental Engineering, Politecnico di Milano, 20133 Milano, Italy
2 Department of Civil Engineering and Construction, Atlantic Technological University Sligo, F91 YW50 Sligo, Ireland; ruth.quinn@atu.ie
3 Department of Civil, Chemical and Environmental Engineering, University of Genova, 16145 Genoa, Italy; ilaria.gnecco@unige.it
4 Faculty of Civil and Environmental Engineering, Technion Institute of Technology, Haifa 32000, Israel; ostfeld@technion.ac.il
* Correspondence: anita.raimondi@polimi.it

1. Introduction

Rainwater harvesting is an ancient water supply practice that still provides a primary water source for a large proportion of the world's population. Interest in the topic is increasing (Figure 1), especially in areas that face challenges posed by the joint effects of urban population growth and climate change [1].

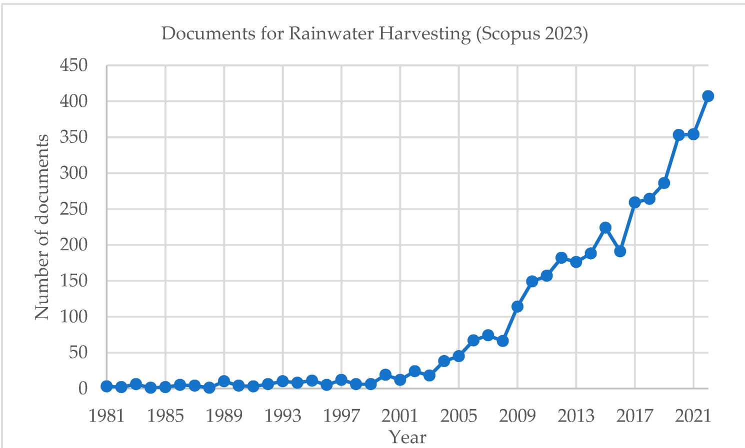

Figure 1. The trend regarding the number of publications indexed in Scopus [2].

This practice is multi-purpose in nature and provides benefits to water supply systems, urban drainage networks, environmental ecosystems, and communities [3]. Rainwater harvesting and reuse provide an alternative source of water supply, for non-potable uses, preserving high-quality sources and preventing potable water waste. It offers a solution to satisfy the increased water demand, due to population growth, especially during periods of scarcity [4]. Rainwater harvesting can improve rainfall runoff control and mitigate flood risk; it reduces peak runoffs and volumes conveyed into sewers and contributes to the achievement of hydrologic invariance goals [5]. In addition, rainwater harvesting can limit the frequency of combined stormwater overflow activation and the discharge of uncontrolled polluted waters into receiving water bodies [6]. Finally, it can reduce energy consumption and greenhouse gas emissions [7].

Depending on the drained surface and the use (domestic, agricultural, industrial, etc.), different treatments can be used to ensure that harvested rainwater meets the required standards. Modern and innovative technologies are available to make rainwater harvesting and reuse more suitable and appealing in different contexts, thus aiding in the growth of this

Citation: Raimondi, A.; Quinn, R.; Gnecco, I.; Ostfeld, A. New Advances in Rainwater Harvesting and Treatment. *Water* **2024**, *16*, 1591. https://doi.org/10.3390/w16111591

Received: 9 May 2024
Accepted: 24 May 2024
Published: 1 June 2024

best management practice, which is fundamental for the transition toward water-sensitive, sustainable, and resilient cities [8].

This Special Issue entitled “Rainwater Harvesting and Treatment” presents a collection of high-quality studies on rainwater harvesting and treatment from esteemed authors hailing from diverse countries. The published papers encompass (a) the technical viability, capability, and economic feasibility of rainwater harvesting systems in different contexts, climatic regions, catchment surfaces, water use scenarios, and system design; (b) stormwater treatment performance by different solutions and techniques and the effects of the first flush phenomenon on stormwater quality degradation; (c) financial support programs to promote the installation of rainwater harvesting systems and increase their economic feasibility; and (d) real-time control of rainwater harvesting systems in multi-purpose management. The papers highlight the significance of comparing the results of developed models with experimental investigations and provide case studies from many countries (Brazil, Italy, Spain, Germany, Egypt, Portugal, Brunei, Turkey, and South Korea).

2. Overview of the Special Issue

Raimondi et al. (2023), introduces the Special Issue with a review paper on the state of the art in rainwater harvesting treatment. The paper highlights the multiple objectives of this best management practice and its environmental and social benefits relative to the Sustainable Development Goals of the UN Agenda 2030. It describes laws and regulations that encourage rainwater harvesting and their current limitations; methodologies for the design of a rainwater harvesting system; the influence of design variables and the impact of time and spatial scales on the system’s performance; the most advanced technologies for rainwater treatment; and trends and perspectives for increasing rainwater harvesting, water reuse, and effective management.

Borgert and Ghisi (2024), Contribution #1, analyzed the technical viability and economic feasibility of rainwater harvesting systems for single- and multifamily residential buildings in Florianópolis (Brazil). Simulations were conducted for representative buildings in the city under different water use scenarios and system designs, with a total of 36 simulation scenarios. The economic analysis was performed for four scenarios over twenty years. The feasibility indicators considered were the net present value, internal rate of return, and payback; the analysis included both initial and operational costs. The intervention was economically feasible for between 60.1% and 74.8% of houses, achieving a discounted payback period of between 6.2 and 8.6 years. For flats, the economic feasibility ranged between 57.8% and 64.2%, with a discounted payback period varying from 4.8 to 5.6 years. The authors compared the former and current tariff formats recently introduced in the city. The current tariff format provided more significant economic benefits by saving potable water, leading to a higher net present value and a shorter discounted payback period.

Niazkar et al. (2024), Contribution #2, evaluated the effects of the first flush phenomenon on stormwater quality degradation through experimental-based investigations. The study presents the outcomes of a two-year field campaign in northern Italy. For the 16 stormwater events observed in the period, water quality analytics and various hydrometeorological variables, including precipitation, flow rate, temperature, and solar radiation, were monitored. For first flush identification, five well-known indices in the literature were calculated. The results indicated a strong positive correlation among mass–first flush ratios calculated for nutrients and the maximum rainfall intensity, maximum flow rate, and antecedent dry weather period. By contrast, rainfall duration exhibited a strong negative correlation with the mass–first flush ratios calculated for nutrients. Furthermore, different macro groups of pollutants behaved differently. Their findings highlight the significance of experimental monitoring campaigns in the evaluation of first flush impacts on stormwater quality.

Altobelli et al. (2024), Contribution #3, pointed to the significance of a real-time control system (RTC) for stormwater detention basins to meet the requirements for non-potable use and, at the same time, guarantee the hydraulic protection of the downstream system.

Twenty-seven scenarios were simulated using the numerical model SWMM 5.1. Different types of discharge controls were considered based on rainfall forecast and the water level in the tank. The non-drinking water-saving efficiency ranged from a minimum of 32% to a maximum of 90%; the reduction in the discharged volumes was between 11% and 31%, while the peak flow rate varied more significantly depending on the type of control.

Pedretti et al. (2023), Contribution #4, investigated the potential of rainwater harvesting to increase freshwater availability in isolated households. The case study focused on the island of Ibiza (Spain), which suffers from a lack of freshwater due to persistent and recurring droughts, limited groundwater availability, and mass tourism. The study considered an innovative modular tank of 40 m^3 buried in the garden of a private property to intercept runoff from a 12,300 m^2 hilly microcatchment. An extreme rainfall event with an intensity of 65 mm/h fills up the tank in one hour. A curve-number-based rainfall-runoff model was used to simulate the experimental results and estimate the potential of rainwater harvesting at the island scale. The analysis indicated that if all forest areas in Ibiza with a similar slope to the study area were considered, a volume of 1.31×10^6 m^3 of freshwater could be harvested per year merely from extreme precipitation events. Such a volume is equivalent to about 5% of the island's total freshwater budget.

Hendy et al. (2023), Contribution #5, evaluated the treatment performance of real-scale vertical flow-constructed wetlands for wastewater treatment in rural areas. The efficiencies of three different units, comprising Paulownia trees, Phragmites Australis, and one unplanted unit used as a control, were compared in the experiments. Both Paulownia and Phragmites Australis significantly reduced the levels of COD and BOD_5, with removal percentages ranging from 57.1% to 98% for COD and 49.1% to 98% for BOD_5. The authors concluded that the efficiency of constructed wetlands can be significantly enhanced by the presence of suitable plant species.

Köster et al. (2023), Contribution #6, proposed the concept of "City Water Hubs," decentralized treatment units to collect and treat rainwater from nearby rooftops. They are equipped with low-energy technologies to develop various customized "city water" qualities and store rainwater until it is used or distributed. The study presents a feasibility analysis in the campus area at the main building of the Leibniz University of Hannover (Germany), and the results on rainwater qualities from investigations with two pilot plants consisting of a gravity-driven membrane filtration and a slow sand filter with an integrated activated carbon layer are presented. Their study reveals that sufficient rainwater for irrigation purposes can be provided for the university park even under extreme dry and heat wave conditions. If large portions of the roof area (11,737 m^2) of the main building were used for rainwater collection, even in a dry year with only 49.8% of average precipitation, only 19.8% of the harvested stormwater would be needed for irrigation. The quality analysis of rainwater samples showed TSS concentrations of up to 7.54 mg/L, COD concentrations of up to 58.5 mg/L, and NH4 concentrations of up to 2.21 mg/L, which are in line with data reported in the literature.

Monteiro et al. (2023), Contribution #7, focused on the significance of establishing the runoff coefficient values in newly installed green roofs using feasible models able to simulate the retention behavior as realistically as possible and adjust to the season and climate region. They assessed the suitability of a previously developed model for the determination of runoff coefficient by using experimental data registered over a 1-year period. The results showed that the previously developed model did not fit well with the experimental data obtained in the present study, since it neglected some important variables such as early-stage moisture conditions of the green roof matrix and the time scale of the process. The pilot extensive green roof with an area of 0.4 m^2 presented an annual retention volume of 469.3 L, corresponding to a retention rate of 89.6%, in a year with a total precipitation of 1089 mm.

Kapli et al. (2023), Contribution #8, performed a feasibility analysis of an open-pond rainwater harvesting system for ablution purposes in Brunei Darussalam. The authors evaluated the quality of harvested rainwater and formulated a rainwater harvesting model with suitable performance measures that can be used in any locality by inputting local meteorological data. Quality analysis revealed that the harvested rainwater can be used safely for ablution purposes, albeit with a slightly acidic pH below 6.5. At a depth of 1.0 m and using the current pond configuration of a local mosque, the reliability of the system was 62.5% (228 days per year), and the amount of water saved was 345 m^3, corresponding to 60.7% of the water demand. It was found that a pond surface area of 60–70 m^2 would provide optimum reliability and water savings, which can be further improved with a more economical usage of water during ablution.

Istchuk and Ghisi (2023), Contribution #9, evaluated the influence of rainfall time series indicators (average annual rainfall, seasonality index, and dry periods) and design variables (catchment area, rainwater demand, number of inhabitants, potable water demand, and rainwater tank size) on the financial feasibility of rainwater harvesting systems in eight Brazilian cities. Correlations between rainfall indicators and financial feasibility were introduced, along with sensitivity analyses of design variables. Financial feasibility ranged from 30% to 70% in the simulated scenarios. Initial investment and operating costs varied significantly among the eight cities, according to local prices. Systems with a catchment area of 200 m^2 facilitate the supply of, on average, 90.5% of the maximum rainwater consumption. The number of inhabitants and the size of the rainwater tank were the most influential design variables regarding financial feasibility, which was also affected by variations in potable water tariffs in different locales, rainfall seasonality indexes, and dry period duration.

Jin et al. (2023), Contribution #10, evaluated financial support programs aimed at promoting the installation of rainwater harvesting systems and increasing their economic feasibility. Based on a cost–benefit analysis, capacity optimization methods were suggested. They performed a sensitivity analysis to determine the relative importance of uncertain parameters such as inflation and discount rates for the identification of additional priority factors in the design of rainwater harvesting systems. The net present value, although sensitive to the inflation rate, was found to be more appropriate for estimating the economic efficiency of a rainwater harvesting system than the typical cost–benefit ratio. Moreover, a proper inflation rate should be considered for the economic feasibility of rainwater harvesting systems. A funding program can significantly increase the benefits and ensure the economic feasibility of the intervention.

Ertop et al. (2023), Contribution #11, assessed the amount of rainwater supplied in greenhouse areas in Antalya (Turkey), where about half of the greenhouses of the counties are located. The total amount of stormwater harvested with greenhouse roofs was estimated to be 224,992,795.8 m^3 per year. Monthly calculations over the year showed that the minimum stormwater amount can be harvested in August (938,447.53 m^3) and the maximum (54,771,210 m^3) in December. They concluded that a large amount of plant water consumption can be provided through rainwater harvesting from greenhouse roofs.

3. Conclusions

The papers included in this Special Issue of *Water*, entitled "Rainwater Harvesting and Treatment", provide a contemporary snapshot of research trends in the field. Each of the twelve research papers contributes to the advancement of the topic with an in-depth investigation of a specific feature, offering a comprehensive overview of recent advances in rainwater harvesting and treatment and presenting an extensive array of research interesting to readers.

Author Contributions: Conceptualization, A.R.; investigation, A.R.; writing—original draft preparation, A.R.; writing—review and editing, A.R., A.O., R.Q. and I.G.; supervision, A.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflicts of interest.

List of Contributions

1. Borgert, A.E.; Ghisi, E. The Impact of the Water Tariff on the Economic Feasibility of Rainwater Harvesting for Use in Residential Buildings. *Water* **2024**, *16*, 1058. https://doi.org/10.3390/w16071058.
2. Niazkar, M.; Evangelisti, M.; Peruzzi, C.; Galli, A.; Maglionico, M.; Masseroni, D. Investigating First Flush Occurrence in Agro-Urban Environments in Northern Italy. *Water* **2024**, *16*, 891. https://doi.org/10.3390/w16060891.
3. Altobelli, M.; Evangelisti, M.; Maglionico, M. Multi-Objective Performance of Detention Basins and Rainwater Harvesting Systems Using Real-Time Controls with Rainfall Forecasts. *Water* **2024**, *16*, 71. https://doi.org/10.3390/w16010071.
4. Pedretti, D.; Roig Palomeque, I.; Meier, S. Ground-Runoff Harvesting to Increase Water Availability in Isolated Households on Hilly Mediterranean Islands: A Case Study in a Micro-Catchment of Ibiza (Spain). *Water* **2023**, *15*, 4317. https://doi.org/10.3390/w15244317.
5. Hendy, I.; Zelenakova, M.; Pietrucha-Urbanik, K.; Salama, Y.; Abu-hashim, M. Decentralized Constructed Wetlands for Wastewater Treatment in Rural and Remote Areas of Semi-arid Regions. *Water* **2023**, *15*, 2281. https://doi.org/10.3390/w15122281.
6. Köster, S.; Hadler, G.; Opitz, L.; Thoms, A. Using Stormwater in a Sponge City as a New Wing of Urban Water Supply—A Case Study. *Water* **2023**, *15*, 1893. https://doi.org/10.3390/w15101893.
7. Monteiro, C.M.; Santos, C.; Castro, P.M.L. Extensive Green Roofs: Different Time Approaches to Runoff Coefficient Determination. *Water* **2023**, *15*, 1852. https://doi.org/10.3390/w15101852.
8. Kapli, F.W.A.; Azis, F.A.; Suhaimi, H.; Shamsuddin, N.; Abas, P.E. Feasibility Studies of Rainwater Harvesting System for Ablution Purposes. *Water* **2023**, *15*, 1686. https://doi.org/10.3390/w15091686.
9. Istchuk, R.N.; Ghisi, E. Influence of Design Variables on the Financial Feasibility of Rainwater Harvesting Systems. *Water* **2023**, *15*, 1112. https://doi.org/10.3390/w15061112.
10. Jin, Y.; Lee, S.; Kang, T.; Park, J.; Kim, Y. Capacity Optimization of Rainwater Harvesting Systems Based on a Cost–Benefit Analysis: A Financial Support Program Review and Parametric Sensitivity Analysis. *Water* **2023**, *15*, 186. https://doi.org/10.3390/w15010186.
11. Ertop, H.; Kocięcka, J.; Atilgan, A.; Liberacki, D.; Niemiec, M.; Rolbiecki, R. The Importance of Rainwater Harvesting and Its Usage Possibilities: Antalya Example (Turkey). *Water* **2023**, *15*, 2194. https://doi.org/10.3390/w15122194.

References

1. Rosenberger, L.; Leandro, J.; Pauleit, S.; Erlwein, S. Sustainable stormwater management under the impact of climate change and urban densification. *J. Hydrol.* **2021**, *596*, 126137. [CrossRef]
2. Raimondi, A.; Quinn, R.; Abhijith, G.R.; Becciu, G.; Ostfeld, A. Rainwater Harvesting and Treatment: State of the Art and Perspectives. *Water* **2023**, *15*, 1518. [CrossRef]
3. Campisano, A.; Butler, D.; Ward, S.; Burns, M.J.; Friedler, E.; DeBusk, K.; Fisher-Jeffes, L.N.; Ghisi, E.; Rahman, A.; Furumai, H.; et al. Urban rainwater harvesting systems: Research, implementation and future perspectives. *Water Res.* **2017**, *115*, 195–209. [CrossRef] [PubMed]
4. Tran, S.H.; Dang, H.T.; Dao, D.A.; Nguyen, V.A.; Nguyen, L.T.; Nguyen, V.A.; Han, M. On-site rainwater harvesting and treatment for drinking water supply: Assessment of cost and technical issues. *Environ. Sci. Pollut. Res.* **2021**, *28*, 11928–11941. [CrossRef] [PubMed]
5. Palla, A.; Gnecco, I. On the Effectiveness of Domestic Rainwater Harvesting Systems to Support Urban Flood Resilience. *Water Resour. Manag.* **2022**, *36*, 5897–5914. [CrossRef]
6. Ghodsi, S.H.; Zhu, Z.; Matott, L.S.; Rabideau, A.J.; Torres, M.N. Optimal siting of rainwater harvesting systems for reducing combined sewer overflows at city scale. *Water Res.* **2023**, *230*, 119533. [CrossRef] [PubMed]
7. de Sá Silva, A.C.R.; Bimbato, A.M.; Balestieri, J.A.P.; Vilanova, M.R.N. Exploring environmental, economic and social aspects of rainwater harvesting systems: A review. *Sustain. Cities Soc.* **2022**, *76*, 103475. [CrossRef]
8. Feng, W.; Liu, Y.; Gao, L. Stormwater treatment for reuse: Current practice and future development—A review. *J. Environ. Manag.* **2022**, *301*, 113830. [CrossRef] [PubMed]