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Water Quality Improvement through Rainwater Tanks: A Review and Simulation Study

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Abstract: First, this paper presents a thorough review of water quality data using a rainwater tank, categorizing the data as with and without sedimentation. Data are presented showing minimum, maximum, and mean values for the different parameters. The data measured from several sources reveal that water collected from the tank is much better than the water directly collected from the roof. In addition, to analyse the phenomena through a mathematical model, a hypothetical 5 kL rainwater tank with a 200 m^2 roof was modelled with the MUSIC model. The simulations were compared with the measured water quality data from a rainwater tank in Melbourne. In general, we found that MUSIC's simulations on the mean daily concentrations of total suspended solids (TSS) and total phosphorus (TP) are slight underestimations compared to the measured data from Melbourne. Further MUSIC simulations reveal that significant reductions in the daily maximum concentrations of TSS, TP, and total nitrogen (TN) are expected through a rainwater tank.

Keywords: total suspended solids; total phosphorus; total nitrogen; MUSIC

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Citation: Imteaz, M.A.; Boulomytis, V.T.G.; Yilmaz, A.G.; Shanableh, A. Water Quality Improvement through Rainwater Tanks: A Review and Simulation Study. *Water* **2022**, *14*, 1411. https://doi.org/10.3390/w14091411

Academic Editor: Marco Franchini

Received: 7 April 2022
Accepted: 26 April 2022
Published: 28 April 2022

1. Introduction

Rainwater tanks have been in use for many centuries in non-arid regions. Traditionally, it is the prime source of water for many remote communities where there is no other suitable water source. Such remote communities even use rainwater for potable purposes after having some basic treatments. Recently, given the tremendous increase in population and the limited sources of potable water, urban water authorities are adopting several measures including demand management and identifying alternative water sources such as stormwater harvesting, grey water, and wastewater reuse. Among all the alternative water sources, stormwater harvesting is the most suitable and easily achievable. Despite having centralised water supply systems, modern urban communities have started adopting rainwater tanks, mainly for non-potable purposes. As such, the original focus of rainwater tanks as being only a means of water supply has shifted to being an alternate source of water augmentation. In Australia, federal, state, and local government authorities have been promoting stormwater harvesting through campaigns as well as offering financial incentives and grants to promote the implementation of such water saving methodologies.

There have been numerous studies on rainwater tanks, with many treating rainwater harvesting potentials or quantifications, among which some recent ones are Imteaz et al. [1], Khan et al. [2], Santos et al. [3], and Imteaz and Moniruzzaman [4]. Continuing from water harvesting potentials, some other studies have investigated the reliability and financial benefits related to rainwater tanks [5–7]. There are several studies that have investigated the quality of harvested/captured rainwater, as in many cases, it is used for potable purposes. Boulomytis [8] assessed the quality of harvested rainwater over clay tiles in Brazil, analysing the turbidity, colour, and pH parameters. The author found that due to the antecedent drought prior to the first intense rainfall, the quality of the first flush was poor due to the contaminants initially spread over the roof. However, the samples collected after 30 min had sufficient quality to be used for the purpose of primary food irrigation (e.g., lettuce), in keeping with the potability standards of the Brazilian Federal Law. Farreny et al. [9] investigated the effect of different types of roofs, taking into consideration factors such as the roof slope and material. In addition to investigating the effects on runoff quantity, they have also investigated the physicochemical characteristics of the collected rainwater from different types of roofs. They have reported that sloping roofs provide better quality runoff compared to flat roofs in regard to some of the tested parameters (conductivity, total organic carbon, and total carbonates except for ammonium). Lee et al. [10] investigated the effect of different types of roof material on runoff water quality in South Korea. Among the tested roofing materials (i.e., wooden shingle tiles, concrete tiles, clay tiles, and galvanized steel), they have found that galvanized steel provides the most suitable runoff quality and that even the collected rainwater meets the Korean drinking water quality standard regarding the pH, TSS, NO_3, SO_4, Al, Cu, Fe, Pb, Zn, and *E. coli*. Rahman et al. [11] investigated the quality of harvested rainwater on several occasions within a year in Bangladesh. They reported that the quality of harvested water is satisfactory and fulfils the potable water standard for Bangladesh in regard to faecal coliform, total coliform, total suspended solids (TSS), turbidity, NH3–N, lead, and BOD_5. Charters et al. [12] investigated stormwater runoff quality from different impervious surfaces including roads and roofs of different materials. They have found that the road surface produces the highest concentrations of TSS, while the highest copper and zinc concentrations are drained from copper and galvanized roofs, respectively. Obviously, these copper and zinc concentrations are derived from the dissolution of copper and galvanized roofing materials. They have also found that the concentrations of pollutants are much higher in the first samples (i.e., first flush). Leong et al. [13] have monitored harvested rainwater quality in six different sites in Malaysia for a period of 8 months. They have reported that the harvested rainwater is not suitable for drinking. However, it was suitable for recreational purposes, although on some occasions it did not even meet the criteria of recreational water in regard to pH, ammonia, phosphates, and total coliforms.

Many of the above-mentioned studies considered the quality of stormwater at the first flush stored in a first-flush diverter. Quality of stormwater at first flush is expected to be much inferior compared to the subsequent collections, as a first-flush diverter is provided to capture higher concentrations of pollutants accumulated from antecedent dry days. However, none of the studies considered treatment and improvement of stormwater quality within the tank. As the harvested water stays within the tank, the sediments tend to settle at the bottom of the tank. Because some nutrients are attached to the sediment particles, settlements of sediments also result in settlements of some nutrients. Moreover, several bacteria are likely to die within the tank after a few days due to a lack of food (i.e., organic matter), if the stored rainwater was not highly enriched with organic matters. With the aim of investigating this phenomenon, earlier rainwater samples collected directly from the roof and from the tank were tested, and similar results were reported by Imteaz et al. [14]. To ascertain such conclusions, this study aimed to thoroughly review the existing literature on the qualities of harvested rainwater from two different sources, i.e., roof and tank, and then to analyse such segregated rainwater quality data to establish the water quality benefit of rainwater tanks. Additionally, the experimental measurements were compared through a mathematical modelling study on the same phenomena applying the widely used simulation software titled Modelling for Urban Stormwater Improvement Conceptualisation, MUSIC [15]. In the past, there were several studies on the experimental measurements of rainwater quality from the roof and/or tank. However, no study has verified such measurements through the simulation model.

2. Methodology

A thorough review of the literature was conducted on the water quality of rainwater harvested through rainwater tanks. Extracted results on the rainwater quality were separated based on the sample collection points, i.e., directly from the roof and/or from the tank. Some studies were conducted solely with the water from the roof, while some other studies were only conducted with the water from the tank. The results from these sole sources were summarised and discussed. In addition, from each study, minimum, maximum, and mean values of the particular water quality parameters were reported. There are some studies that investigated the rainwater qualities both from the roof and from the tank. For the studies that considered both rainwater sample collection points, the improvement (I) in rainwater through sedimentation, which took into consideration the water quality without sedimentation (WQ_{NS}) and with sedimentation (WQ_{WS}), was calculated using the following equation; note that the outcome from the equation is unitless insofar as the unit of other parameters is usually "mg/L" and may vary depending on the selected water quality parameter:

$$I\ (\%) = \frac{WQ_{NS} - WQ_{WS}}{WQ_{NS}} \quad (1)$$

The experimental findings on these phenomena were compared with a typical mathematical modelling analysis. For the mathematical modelling analysis, the widely used Australian tool MUSIC (Version 6HL) was used. The measurements conducted by Imteaz et al. [14] were used for the comparison, as the MUSIC model was predominantly developed for the Australian environment, incorporating several default parameters that were derived from the Australian catchments.

MUSIC is able to simulate both the quantity and quality of runoff from different types (urban, agricultural, and forest) of catchments. For the current study, the catchment was assumed as urban, having a 100% impervious surface (i.e., roof). Additionally, MUSIC is able to model different types of treatment processes used for typical urban stormwater [16]. MUSIC's simulations can be event-based or on a continuous basis, which allows for comprehensive analysis and comparisons between short-term and long-term benefits of any stormwater treatment system. Duncan [17] conducted a comprehensive review of stormwater quality in urban catchments, which formed the basis of the default values used in MUSIC and provided default values of the event mean concentrations (EMC) of TSS, total phosphorus (TP), and total nitrogen (TN). In addition to simulating the above-mentioned pollutants including the gross pollutants, MUSIC is able to simulate treatment efficiencies through gross pollutant traps, grassed swale, sand filter, bioretention system, wetland, and sedimentation basin. It can also simulate treatments and flow attenuations through rainwater tanks. The latest version of MUSIC is named as MUSICX, details regarding which are available from eWater [18]. Although primarily developed for Australian catchments, MUSIC has been used in some other countries. Imteaz et al. [19] tested MUSIC using measurements from different treatment systems constructed in Australia, Sweden, New Zealand, and Scotland.

Eventually, the simulations from MUSIC are presented as cumulative frequency curves comparing inflow (to the rainwater tank) and outflow (from the rainwater tank) water concentrations of TSS, TP, and TN, which in fact reveal the treatment efficiencies theoretically expected to be achieved through a rainwater tank.

3. Results

Experimental measurement data focusing on water quality data from rainwater tanks and from roofs used in different countries are collected from the existing literature. The collected measurements were categorised as before sedimentation (the sample collected from the roof) and after sedimentation (the sample collected from the rainwater tank). A wide variety of parameters has been used by different researchers. The following section elaborates on the summaries of the measurements, showing minimum, maximum, and mean values of the selected water quality parameters.

3.1. Review on Measured Water Quality Data

The summary of the reported TSS measurements from different countries are categorised in Table 1 as with (i.e., after) or without (i.e., before) sedimentation. We considered a broad variety of concentrations, such as the TSS concentration of rain water or rain water drained through the roof, as well as how these were influenced by many factors, such as the geographical location, the proximity to urban/industrial activities or high traffic roads, and the roof type. It is not possible to generalise the results of such varied pollutant concentrations. However, in every case, it was commonly observed that the TSS concentration significantly dropped in the samples taken after sedimentation. In the samples without sedimentation, the range of maximum TSS observed was 10–425 mg/L. However, in the samples with sedimentation, the range of maximum TSS was 5–379 mg/L. Except for the case of Sweden, in all other cases, the maximum TSS concentrations after sedimentation were less than half of the TSS concentrations without sedimentation.

Table 1. Measurements on TSS concentration.

Country	TSS Concentration (mg/L)						Reference
	with Sedimentation			without Sedimentation			
	Min	Max	Mean	Min	Max	Mean	
Australia *	-	-	<5.00	-	-	10.00	Imteaz et al. [14]
Greece	1.40	4.20	2.60	9.50	39.50	16.52	Gikas and Tsihrintzis [20]
Korea	0.20	0.65	0.42	130.00	425.00	236.00	Lee et al. [10]
Malaysia	0	46.00	4.08	-	-	-	Leong et al. [13]
Singapore	2.50	67.00	9.10	-	-	-	Appan [21]
Spain	0	38.50	5.98	-	-	-	Farreny et al. [9]
Sweden	33.00	379.00	220.00	60.00	421.00	227.00	Villareal and Dixon [22]
USA	12.50	62.50	39.00	20.00	220.00	50.00	Mendez et al. [23]

* Melbourne.

Table 2 shows the summary of the reported TP concentrations in the samples, though only two studies reported concentrations before and after sedimentation. In general, the concentrations of TP varied from 0.04 to 2.94 mg/L in the samples without sedimentation, whereas the same concentration varied from 0.03 to 1.01 mg/L in the samples with sedimentation. Similar reductions are observed in the case of the TN concentrations (Table 3). For samples without sedimentation, the TN concentrations varied from 0.64 to 2.4 mg/L, whereas for samples with sedimentation, it varied from 0.15 to 2.80 mg/L. For the studies where both the samples with and without sedimentation were considered, 16–94% reductions in mean TN concentration in the outflow samples were observed.

Table 2. Measurements on TP concentration.

Country	TP Concentration (mg/L)						Reference
	with Sedimentation			without Sedimentation			
	Min	Max	Mean	Min	Max	Mean	
Australia *	-	-	0.03	-	-	0.04	Imteaz et al. [4]
France	0.10	0.54	0.17	-	-	-	Vialle et al. [24]
Greece	0.64	1.37	1.01	1.21	7.16	2.94	Gikas and Tsihrintzis [20]
Malaysia	0	3.70	0.20	-	-	-	Leong et al. [13]
Singapore	0	4.30	0.10	-	-	-	Appan [21]
Spain	0	6.60	0.32	-	-	-	Farreny et al. [9]

* Melbourne.

Table 3. Measurements on TN concentration.

Country	TN Concentration (mg/L)						Reference
	with Sedimentation			without Sedimentation			
	Min	Max	Mean	Min	Max	Mean	
Canada	0.30	2.30	1.26	-	-	-	Despins et al. [25]
France	0.54	7.80	2.80	-	-	-	Vialle et al. [24]
Greece	0.36	0.68	0.54	0.58	0.84	0.64	Gikas and Tsihrintzis [20]
Korea	0	0.30	0.15	0.62	4.40	2.40	Lee et al. [10]
New Zealand	1.50	4.50	2.60	-	-	-	Pennington and Webster-Brown [26]
Spain	0.01	9.34	1.75	-	-	-	Farreny et al. [9]
USA	0.47	1.50	1.18	1.00	3.30	1.80	Mendez et al. [23]
Vietnam	0.10	8.60	0.96	-	-	-	Lee et al. [27]

Regarding the total dissolved solids (TDS), few studies considered this pollutant, as shown in Table 4. Among the few found, only Rahman et al. [11] considered samples from both with and without sedimentation, finding a 37% reduction in the mean TDS concentration after sedimentation.

Table 4. Measurements on TDS concentration.

Country	TDS Concentration (mg/L)						Reference
	with Sedimentation			without Sedimentation			
	Min	Max	Mean	Min	Max	Mean	
Bangladesh	10.00	75.00	27.38	10.00	190.00	43.58	Rahman et al. [11]
Malaysia	0	139.00	33.72	-	-	-	Leong et al. [13]
Singapore	12.50	19.50	15.61	-	-	-	Appan [21]
Vietnam	26.00	404.20	48.60	-	-	-	Lee et al. [27]

Among the metals, Tables 5 and 6 show the concentrations of lead and zinc, respectively, in the samples with and without sedimentation. As for the concentrations of lead, among the measurable values, reductions from 33% to 64% were observed through sedimentation. For zinc, reductions from 30% to 75% were observed through sedimentation. Apart from the mentioned pollutants, Imteaz et al. [14] reported a 33% reduction in the mean copper concentration and a >38% reduction in chemical oxygen demand (COD) concentration through sedimentation.

Table 5. Measurements on lead concentration.

Country	Lead Concentration (mg/L)						Reference
	with Sedimentation			without Sedimentation			
	Min	Max	Mean	Min	Max	Mean	
Australia *	-	-	<0.0010	-	-	0.0010	Imteaz et al. [4]
Bangladesh	0.0100	0.0300	0.0200	0.0130	0.0480	0.0300	Rahman et al. [11]
Korea	0.0040	0.0080	0.0050	0.0130	0.0220	0.0140	Lee et al. [10]
Malaysia	0	0.1100	0.0100	-	-	-	Leong et al. [13]
USA	0.0003	0.0086	0.0023	-	-	-	Mendez et al. [23]
Vietnam	0.0010	0.0030	0.0010	-	-	-	Lee et al. [27]

* Melbourne.

Table 6. Measurements on zinc concentration.

Country	Zinc Concentration (mg/L)						Reference
	with Sedimentation			without Sedimentation			
	Min	Max	Mean	Min	Max	Mean	
Australia *	-	-	0.060	-	-	0.090	Imteaz et al. [4]
Korea	0	0.120	0.050	0.170	0.600	0.200	Lee et al. [10]
Malaysia	0	0.320	0.700	-	-	-	Leong et al. [13]
USA	0.001	0.362	0.016	-	-	-	Mendez et al. [23]
Vietnam	0.03	1.460	0.050	-	-	-	Lee et al. [27]

* Melbourne.

It is not possible to generalise such a wide variety of results, and the observed generalised relationships of the reductions are not predictable because they vary significantly with many other factors such as geography, roof material, proximity to urban activities, and rainfall characteristics. However, a mathematical modelling analysis would provide indicative results, which would help authorities make some logical decisions towards implementing such sustainable features. The following section describes generalised analysis using a well-establish water quality model, MUSIC.

3.2. Numerical Simulation Results

A MUSIC model was set up considering a roof of 200 m^2 connected with a rainwater tank of 5 kL. In the MUSIC model, among eleven different surface types, the roof type was exclusively selected with an imperviousness of 100%. MUSIC provides a few years of rainfall data as default data to be used for simulations, while users are allowed to use data from any year provided a complete dataset is available. For this study, a 6 min rainfall data for the year 1969 was selected for Melbourne, as provided with the MUSIC software. For the pollutant generation from the roof surface, the model default mean values were adopted: 19.95 mg/L for TSS, 0.13 mg/L for TP, and 2.0 mg/L for TN. In the model, there is an option for a stochastically generated time series for the estimation of pollutants, which was selected for the current analysis. From different pollutant treatment options provided in the MUSIC, the rainwater tank was selected as a treatment node. Other properties of the selected 5 kL tank were a surface area of 2.5 m^2, a depth above overflow corresponding to 0.05 m, an overflow pipe diameter of 50 mm, and no initial water in the tank. Figure 1 shows the model setup as built in the MUSIC software. The model was simulated for the mentioned rainfall year (i.e., 1969).

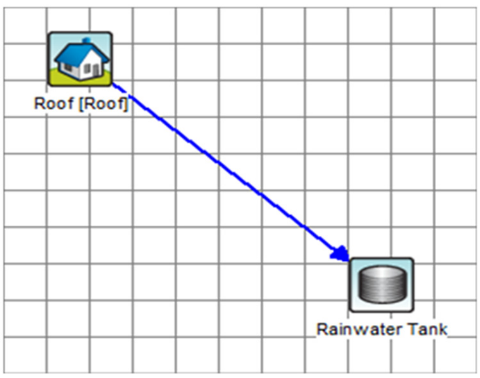

Figure 1. Model setup used in the MUSIC software.

Table 7 shows the model simulated results concerning the daily mean values, daily maxima values, and mean annual loads of TSS, TP, and TN for inflow (to the tank) and outflow (from the tank) water, which can be represented as with and without sedimentation. From Table 7, it is found that in regard to TSS, the reductions in the daily mean concentration and the mean annual load are 44% and 40%, respectively. Regarding the parameter TP, the reductions in the daily mean concentration and the mean annual load are 18% and 12.5%, respectively.

Table 7. Model simulated results with and without sedimentation.

Parameter	TSS			TP			TN		
	Concentration		Reduction (%)	Concentration		Reduction (%)	Concentration		Reduction (%)
	In	Out		In	Out		In	Out	
Daily Mean (mg/L)	6.60	3.69	44.1	0.039	0.032	17.9	0.552	0.478	13.4
Daily Maxima (mg/L)	20.10	3.88	80.7	0.099	0.033	66.7	1.11	0.48	56.8
Mean Annual Load (kg)	3.00	1.79	40.3	0.016	0.014	12.5	0.247	0.212	14.2

For TN, the reductions in the daily mean concentration and the mean annual load are 13% and 14%, respectively. However, about the daily maximum concentration, the reductions are expected to be significant: 81% for TSS, 67% for TP, and 57% for TN. In general, such stochastic results are not comparable with a random measurement, which was performed for the case of water quality measurements conducted for a rainwater tank located in Melbourne as reported by Imteaz et al. [4]. Nonetheless, the random measurements conducted for the Melbourne rainwater tank revealed more than a 50% reduction in TSS and a 25% reduction in TP, which are comparable with reductions in the daily mean concentrations as per MUSIC. Regarding the daily mean concentrations, MUSIC simulated a 44% reduction in TSS and an 18% reduction in TP. Though both the simulated results are close to random measurements, MUSIC slightly underestimated the water quality improvements compared to the real measurements. It was not possible to compare MUSIC's prediction regarding TN concentration reduction because in the selected case study, the TN was not measured.

To further visualise the expected water quality benefits, MUSIC simulation results are presented as cumulative frequency curves for daily maximum and daily mean concentrations. Figure 2 shows the frequency curves for the daily maximum concentrations and reveals significant reductions in TSS, TP, and TN daily maximum concentrations. For TSS (Figure 2a), the daily maximum concentration of inflow water is expected to be always less than 200 mg/L, whereas in outflow water, it is expected to be less than 40 mg/L. For TP (Figure 2b), the daily maximum concentration of inflow water is expected to be always less than 0.8 mg/L, whereas in outflow water, it is expected to be less than 0.2 mg/L. For TN (Figure 2c), the daily maximum concentration of inflow water is expected to be always less than 8 mg/L, whereas in outflow water, it is expected to be less than 3 mg/L.

Similar frequency curves for the daily mean concentrations are shown in Figure 3, which reveals moderate reductions in TSS, TP, and TN. For TSS (Figure 3a), the daily mean concentration of inflow water is expected to be always less than 50 mg/L, whereas in outflow water, it is expected to be less than 25 mg/L. For TP (Figure 3b), the daily maximum concentration of inflow water is expected to be always less than 0.24 mg/L, whereas in outflow water, it is expected to be less than 0.16 mg/L. For TN (Figure 3c), the daily maximum concentration of inflow water is expected to be always less than 3.5 mg/L, whereas in outflow water, it is expected to be less than 2.5 mg/L.

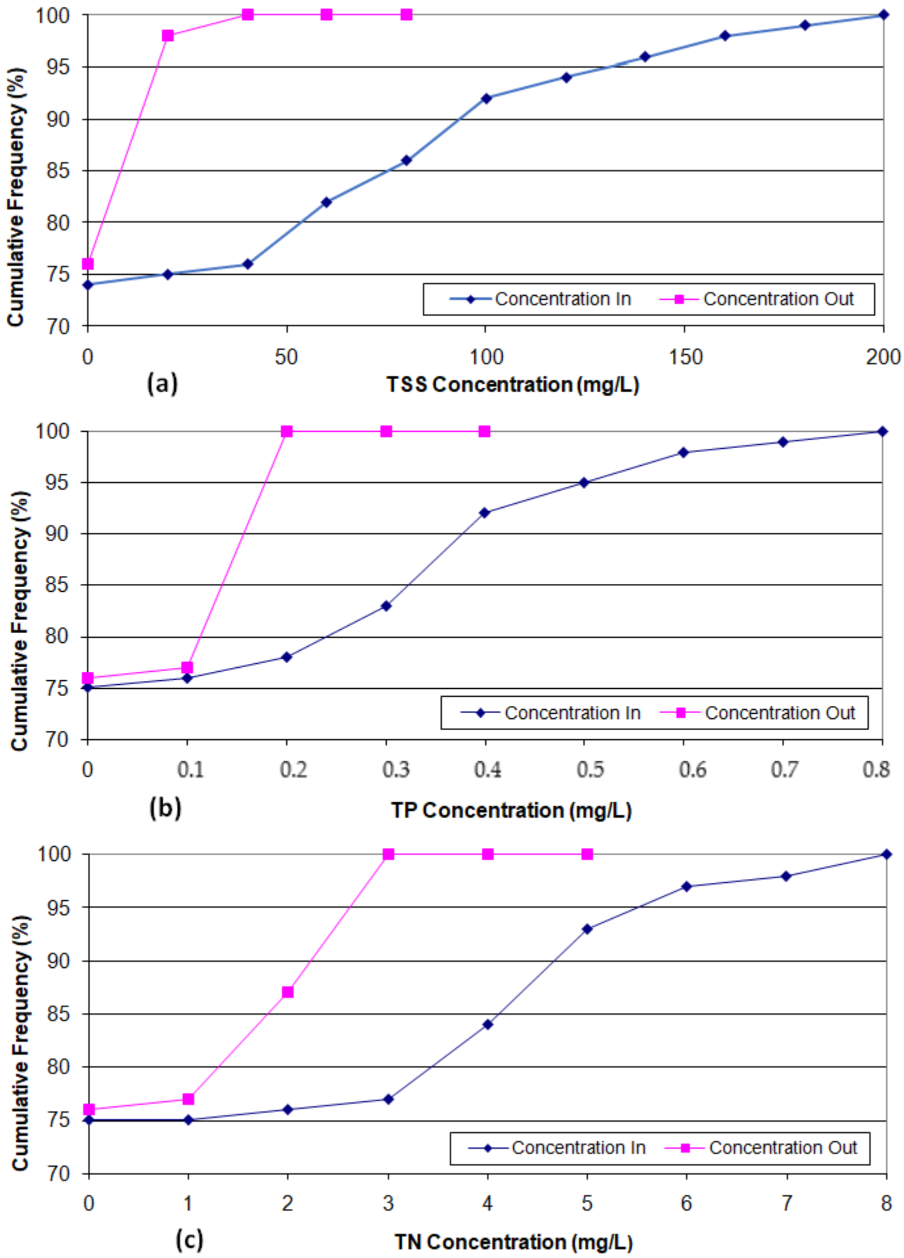

Figure 2. Frequency curves for the daily maximum concentrations of (**a**) TSS, (**b**) TP, and (**c**) TN.

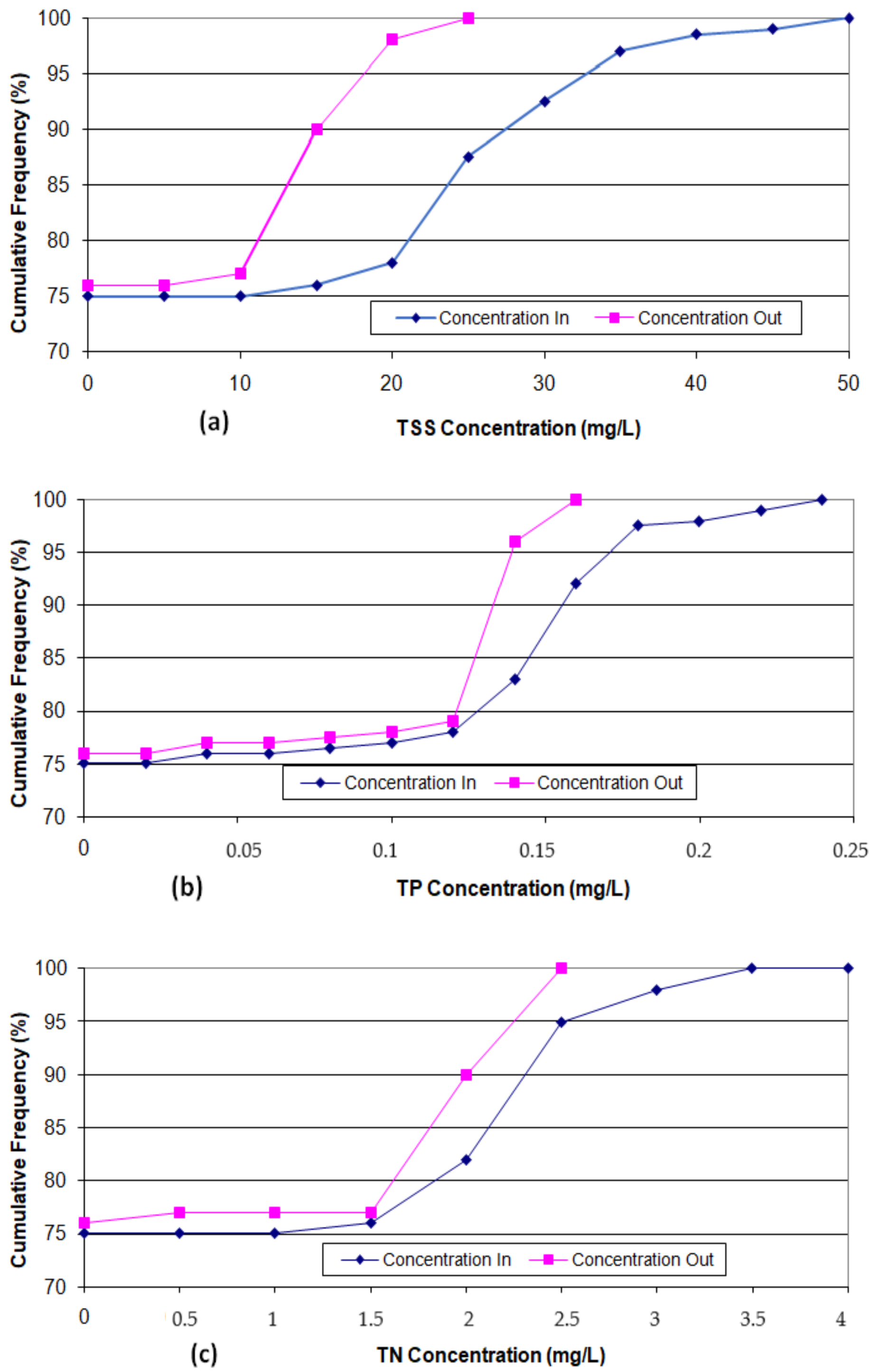

Figure 3. Frequency curves for the daily mean concentrations of (**a**) TSS, (**b**) TP, and (**c**) TN.

4. Discussions

Among the reviewed articles, the tested pollutants were not universal for all the studies. However, we have reviewed measurements from a few of the most common pollutants. Measured pollutant concentrations were presented as minimum, maximum, and mean. From the presented results, it is clear that, except in a few cases, all the pollutant concentrations in the tank water were lower than the corresponding pollutant concentrations in the rainwater from the roof. It is obvious that when water enters into the tank, sediments and heavy particles start falling. Depending on the retention period, the coarser sediments will fall to the bottom of the tank, which will reduce suspended solids in the upper water layer, seeing that water is usually drawn from the upper level (i.e., the outlet tap from the tank is usually placed at approximately 200~300 mm above the tank bottom). As some nutrients and pollutants are attached to the sediments, trapping sediments at the bottom also causes some other nutrients and/or pollutants to be trapped. For the case of TSS from the tanks in Sweden (Table 1), although all the minimum, maximum and mean values were reduced in the tank water, the reduction in the mean value is insignificant. This might be due to the low-retention period in the tank, which was not specified in the literature. Improvement in the tank water heavily depends on the retention period of the rainwater, i.e., the retention period of rainwater in the tank before it is sampled for testing or used. It is to be noted that improvement of rainwater through storing and sedimentation in the tank will be largely influenced by the tank material. However, this matter was not investigated in this study due to a lack of tank material data from the collected literature. Additionally, MUSIC does not consider such a factor in its simulation of rainwater quality through tanks.

5. Conclusions

This paper investigates the effectiveness of rainwater tanks in treating different pollutants through a comprehensive review of the literature on measured water quality data and mathematical simulations using well-established MUSIC software. For the comparison, water quality measurements, which included rainwater samples to and from rainwater tanks, were considered. As pollutants in the roof-collected rainwater depend on many factors including roof material, proximity to urban activities, and geographical location, wide ranges of different concentrations of pollutants are reported in the literature.

For the comparison with mathematical simulations, measured results from a Melbourne household rainwater tank were selected, as the Melbourne rainfall was adopted in the developed MUSIC model. We found that MUSIC's simulated results concerning the reductions in the mean daily concentrations of TSS and TP are close to the randomly measured reductions in the same pollutants for the Melbourne household tank.

The developed MUSIC model was used for further scenario presentations. From the presented scenario, we found that regarding the reductions in the maximum of the daily mean concentrations, a 50% reduction in TSS, a 33% reduction in TP, and a 29% reduction in TN are expected through a rainwater tank. By contrast, regarding the reductions in the highest daily maximum concentrations with the same rainwater tank, an 80% reduction in TSS, a 75% reduction in TP, and a 63% reduction in TN are expected. It is obvious that TSS reductions are always highest under all scenarios, as TSS is the primary target pollutant to be removed through sedimentation. Nutrient (such as TP and TN) removals are achieved in an indirect way through attachment of some nutrients on the sediment surface, as the efficiency of nutrient removal is always lower than the TSS removal efficiency. Significant reductions in the highest values of the daily maximum concentrations of pollutants are deemed to be important, as in many cases, that is the primary measure for which there are set maximum magnitudes allowed by different environmental regulatory authorities. It is to be noted that the reported findings are valid for the particular roof size of 200 m^2 and the tank size of 5 kL. For different roof and tank sizes, the removal efficiency of the mentioned pollutants is likely to vary, which can be a part of future study.

This study was based on a particular geographical area near central Melbourne in Australia. The results would vary with geographical locations, i.e., with different climatic conditions or, in general, with different rainfall intensities and patterns.

Author Contributions: Project administration, supervision, and final paper preparation, M.A.I.; data collection, and model setup and analysis, A.G.Y.; conceptualization and final paper checking, A.S.; original draft preparation, and writing—review and editing, V.T.G.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data are available from the first author upon request.

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

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