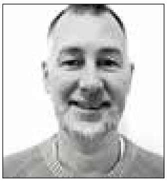
Regnvattenskörd från tak i urbana områden: kvantitet, kvalitet och miljöfördelar

Rainwater harvesting from roof tops in urban areas: Quantity, Quality and environmental benefits



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Abstract

The hydrological cycle is impacted by ongoing climate changes, which in turn affect the local water supply infrastructure due to increasing demands. With the consequences of globalization, it's crucial to ensure access to water of sufficient quality. Utilizing rainwater can ease the pressure on local water supply infrastructure, contributing to adaptation to these changes. Flooding due to extensive downpour can be mitigated by collecting parts of the rainwater. Moreover, when water access is limited to a few locations, it becomes vulnerable to problems such as leaks, contamination, and disasters that can disrupt the supply. This study, based in Malmö, Sweden, investigates the possibilities of rainwater harvesting. The research utilized data gathered by low-cost sensors in the Malmö region, alongside sampling and measurements of rainwater collected from a rooftop. Water samples were subsequently sent to a laboratory for a comparison with the low-cost sensor data. The primary data considerations for this paper included the quantity, quality, environmental benefits, and the economic perspective of rainwater harvesting. The Monte Carlo method was employed to analyse the sensor data. The study revealed that using rainwater in place of serviceable water offers significant environmental advantages, particularly when the demand for high-quality potable water isn't important. Even with low-cost sensors, this research has demonstrated the ability to gather essential data for further evaluation of rainwater usability. There's a need for the continued development of monitoring techniques and methods to qualify water for varied uses. This study has highlighted key components of that process. Additionally, the research resulted in the creation of a water quality index, instrumental in determining the quality of water.

Keywords: 3D-printing; Low-cost sensors; Water shortage; Water quality Index; Water quantity

Sammanfattning

Den hydrologiska cykeln påverkas av pågående klimatförändringar, vilket i sin tur påverkar den lokala infrastrukturen för vattenförsörjning på grund av ökad efterfrågan. På grund av den pågående globaliseringen och urbanisering är det avgörande att säkerställa tillgång till vatten av tillräckligt hög kvalitet. Genom att använda regnvatten kan trycket minska på den lokala vattenförsörjningsinfrastrukturen och bidra till en bättre anpassning till pågående och kommande klimatförändringar. Översvämningar på grund av omfattande skyfall kan mildras genom att en viss mängd av regnvattnet samlas in. Dessutom blir tillgången till vatten sårbar för problem som läckor, föroreningar och katastrofer när den är begränsad till några få platser, vilket kan störa försörjningen.

Denna studie, som är baserad i Malmö, undersöker möjligheterna att samla upp regnvatten. Studien utnyttjade data som samlats in av lågkostnadssensorer i Malmöregionen, tillsammans med provtagningar och mätningar av regnvatten som samlats in från ett hustak. Vattenprover skickades sedan till ett laboratorium för en jämförelse med dessa sensorers mätdata. Viktiga data för denna studie inkluderade kvantitet, kvalitet, miljöfördelar och det ekonomiska perspektivet för uppsamling av regnvatten. Monte Carlo-metoden användes för att analysera sensordata. Studien visade att användning av regnvatten i stället för kommunalt vatten ger betydande miljöfördelar, särskilt när efterfrågan på vatten av hög kvalitet inte är lika viktig. Även med billiga sensorer har denna studie visat att möjligheten att samla in viktiga data för ytterligare utvärdering av regnvattens användbarhet är genomförbart. Det finns behov för fortsatt utveckling av denna metod för att kvalificera vatten för olika användningsområden. Studien har belyst viktiga komponenter för att konkludera vattnets kvalitet. Dessutom resulterade forskningen i skapandet av ett vattenkvalitetsindex, som är användbart för att bestämma

Introduction

The rapid globalization together with the climate changes, both historical and current, are becoming a serious threat to the hydrological cycle. In 1950, about 30% of the earth's inhabitants lived in cities or adjacent to these, which can be compared to 55% in 2018 (UN, 2019). This figure is expected to increase to 68% by 2050 (UN, 2019). According to Akter (2022), there are three major challenges related to water, e.g., floods, over-abstraction of groundwater and a deficit of clean fresh water.

Today, a third of the global population faces water shortage. This is due to enlargement of the urban environment; optimization of the agriculture increases in the industry but also a refined lifestyle. Based on these findings, changes in the hydrological cycle's water flow have emerged as a primary factor contributing to both current and expected water scarcity challenges (Xu & Li, 2020).

In cities, the water stress is increasing today which makes water management problematic (Kuzma, Saccoccia & Chertock, 2023; Lai, 2022). There are several socio-environmental trials underway, including impacts of climate changes on the urban water system, ranging from water supply to wastewater and stormwater management (Brown & Farrelly, 2009; Kourtis & Tsihrintzis, 2021). These challenges include managing the precipitation in a sustainable way as well as adapting the cities to climate change ahead and taking advantage of this water (Suleiman et al., 2020).

The hydrological cycle contains approximately 1.36 billion km^3 of water on Earth (Water Encyclopaedia, 2023) and of that volume, only 0.76% is available as fresh water (USGS, 2019). Precipitation falling on the land surface, is estimated to be 111 thousand km^3 annually and the water cycle flow rate via the groundwater reservoirs is approximate 12 thousand km^3 per year of non-saline fresh water (Slutsky & Yen, 1997). The globally terrestrial evapotranspiration is approximately 65.5 thousand km^3 (Oki & Kanae, 2006). Over the past three decades, the average annual precipitation rate has been 604 mm (Zeng et al., 2012). Over the last thirty years, Zeng et al. (2012) noted that the average annual precipitation rate has been 604 millimetres. The volume of fresh water is approximately 10.5 million km^3, with a turnover time ranging from 1 to 10,000 years, leading to an average turnover time of 5,000 years, as per

Sparrenbom & Jeppsson (2022). The consumption of freshwater for various uses was recorded at 3.99 km^3 in 2014 by Our World in Data (OWID, 2018), and increased to 4.6 km^3 in 2019, as reported by Boretti & Rosa. Furthermore, the withdrawals in 2017 from the groundwater reservoirs were 959 km^3 and these groundwater abstractions accounted for about 25% of the total groundwater outtake (UNESCO, 2022). The changes in the hydrological processes are accelerated by climate change and this can be observed on a global level (Caretta et al., 2022). As a result of this, extreme weather and its consequences will become more frequent and intense in the future (Shadmehri Toosi et al., 2020).

In 2017, approximately one-third of the global population was affected by lack of potable water and about half of the global population was without safe sanitation (McCarton et al., 2021). The different sustainable development goals show how water security, economic growth, climate action, and urban planning are deeply interconnected.

Agriculture's strong reliance on water is indicated by the symbiotic relationship between economic progression and water security. Climate-induced disruptions, such as floods and droughts, can negatively impact agricultural yield. Notably, urban flooding due to climate anomalies costs about US$120 billion globally (McCarton et al., 2021). As the hydrological cycle undergoes changes with rising temperatures and shifting land use, the consequences are seen in water quality, ecosystem health, and overall human well-being.

In this, urban areas face their own challenges. It is estimated that 50% of the world's inhabitants live in cities, many with under-dimensioned water infrastructure, resulting in significant waste of water. One-third of these inhabitants live in unplanned regions, without proper sanitation and clean water facilities (McCarton et al., 2021). The situation emphasises the potential of rainwater harvesting (RWH) to mitigate water stress, offer cleaner water alternatives, and support sanitation.

Financing the transition towards sustainable water management practices and improved infrastructure presents another challenge. According to the World Bank's data from 2016, achieving Sustainable Development Goal 6 (SDG6) by 2030, which includes targets for clean water access, sanitation, and sustainable water use, would require an investment of US$1.7 trillion, amounting to three times the current investment rates.

To meet these challenges, RWH could turn into an important source of fresh water. The rainwater harvesting potential (RWHP) is the rainwater that is maximally available for the human society. RWHP has received great interest from both researchers and politicians lately (Yao et al., 2023).

Firstly, the purpose of this study is to investigate RWH as a complement to existing water supply by investigating the Malmö region where groundwater shortage is a problem. According to the Geological Survey of Sweden (2023), it has been observed that the groundwater levels have been below normal between 2014 and 2023. Secondly, to gain more knowledge about how water from rainwater harvesting can reduce the pressure on freshwater supply and provide rainwater for irrigation of cultivated areas, RWH is of interest. Thirdly, the study investigates if low-cost sensors can contribute to lower cost of water quality measurements and what quantities of conventional water supplies can be replaced by rainwater harvesting. Finally, the study also includes a development of a comprehensive water quality index (WQI). Our article is based on a Master of Science degree report from Mälardalen University, for more details see Collin and Erneland (2023).

METHODS

Water sampling and analysis

The sampling of rainwater was conducted at the property designation Sågen 3 in Malmö, Sweden (Figure 1 1a & 1b). Three water samples intended for chemical analysis were sampled from the drainpipe (Figure 1c) in a 250 ml plastic container (Figure 1d). The samples were collected on February 24, March 13, and April 24, 2023. On February 24, a water sample was also sampled for a biological analysis of the rainwater using a plastic container of 500 ml. Water samples were sent to the laboratory Debe AB in Hägersten for analysis of physical-, chemical and microbiological parameters (Table 1). The laboratory methods that were used for comparing the same parameters as the sensors that was used in the study are seen in Table 2.

Figure 1. Figure 1a shows the property designation, Sågen 3 in Malmö, Sweden. Figure 1b shows the building at Sågen 3. Figure 1c shows a detailed photo of the gutter where sampling took place. Figure 1d displays the sampling container and, consignment box. Photo by Sonny Colin.

The setup for the sensor measurements included two sensor clusters, e.g., the inlet for rainwater, and the filter setup consisting of a bottom layer of sand (200 mm) and a layer of Leca (50 mm) on top. Sensor data were measured by a ESP32 Dev Module from Expressif Systems (2016) and then transferred via Wi-Fi to an Influx database.

Low-Cost Sensors

In this study, a variety of sensors were integrated with the ESP32 device, a microcontroller developed by Expressif Systems. This device has wireless capabilities and analogue input/outputs, with a built-in ADC that handles up to 3.3 V.

All sensors are produced by DF Robot. The pH

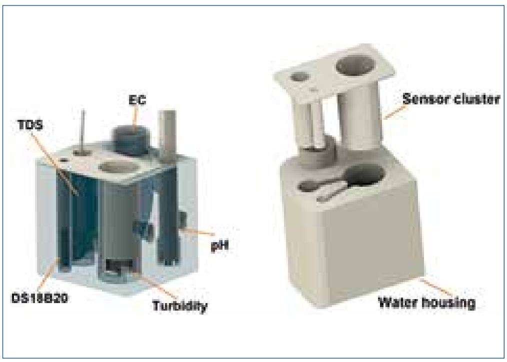

Figure 2. To the left, complete assembly of sensor body and sensor cluster. To the right, sensor cluster and water housing separated (sensor cluster and holder, own illustration, but with DS18B20 sensor by Medina, 2019; TDS sensor by Suresh, 2021; turbidity sensor by Arrieta, 2019 and pH sensor by Happysoft, 2018).

Parameters	Feb	Mar	Apr	Unit
°dH	0.15	0.15	0.45	---
Ca	0.61	0.79	2.6	mg/l
Mg	0.26	0.18	0.40	mg/l
HCO^3	3.17	3.55	6.1	mg/l
Temp	4	4	4	°C
pH	6.6	6.6	6.7	---
Turbidity	0.52	0.63	2.6	FNU
Conductivity	2	2.5	5.3	mS/m
Colour number	8.2	21	47	mg Pt/l
Fe	0.018	0.028	0.045	mg/l
Mn	0.0017	0.002	0.0086	mg/l
COD_{Mn}	0.8	1.9	16	mg O_2/l
Faecal Coliforms	2420	---	---	MPN/100 ml

Table 1. Temp is an approximation for the time of sampling for Malmö. The other parameters are analysed in a laboratory.

Parameters	Method	Uncertainty %	$95_{\%iles}$	WQI
°dH	Ca + Mg	N/A	3.07	1
Ca	SS-EN ISO 17294-2: 2016	20	22.30	1
Mg	SS-EN ISO 17294-2: 2016	20	13.49	1
Turb	SS-EN ISO 7027-1: 2016	40	105.52	3
pH	SS-EN ISO 10523: 2012	0.2	7.84	1
EC	SS-EN ISO 27888: 1994	10	79.71	1

Table 2. The methods used by the laboratory for the parameters, compared with the Malmö data.

sensor has a measurement accuracy of ±0.1 at 25°C while the EC sensor has a corresponding measurement accuracy of ±5% (full scale).

The TDS sensor measures the quantity of soluble solids present in water, indicating the purity of the water. It utilizes a 3.3 V or 5.0 V reference input voltage. The output voltage is converted to a digital reading via the ESP32 Dev Module's 12-bit ADC. The measurement accuracy for the sensor is ±10% of full scale at 25°C.

The turbidity sensor is specialized in measuring turbidity in NTU. The sensor can gauge turbidity levels between 0-3000 NTU. Due to its 5 V input demand, the Arduino MEGA2560 microcontroller was added to the setup.

To measure the temperature, a DS18B20 digital temperature sensor was used. It was connected to the ESP32 Dev Module, recognized for its precision and ease of use. This waterproof sensor has a measurement accuracy of ±0.5°C. All sensors are compatible with either 3.3 V or 5 V. The sensor cluster housing was 3D-modelled and 3D-printed.

Calculation of rainwater properties

To determine the sustainable (RWHP) without negatively impacting the hydrological cycle, the water balance equation was employed.

Precipitation values are taken from Table 3. Evapotranspiration (ET) is estimated from potential evapotranspiration (PE) using Thornthwaite's method, which Sparrenbom & Jeppsson (2022) describe. This method calculates PE based on average temperature and daylight hours, per month and per year, focusing on the energy available for evaporation and transpiration. However, it simplifies by not accounting for water availability or plant characteristics. Actual ET may be lower than PE due to water constraints, and adjustments for these, is not considered by Thornthwaite's direct methodology. Another method, the Penman method, requires more meteorological input than Thornthwaite's method as it also considers parameters such as wind speed, albedo, humidity, and solar radiation (Sparrenbom & Jeppsson, 2022). In this study it was only Thornthwaite´s method that was used.

Groundwater recharge in the calculations, only considers surface water (R), while groundwater runoff is excluded (Colin & Erneland, 2023). The runoff for Malmö was estimated from two areas e.g., areas 90 and 99 according to SMHI (2022). The land area for Malmö is 156.95 km^2 (SCB, 2022). According to Statistics of Sweden (2021), 45.4% of this area (A) is either built up or is landscaped.

From the TDS sensor the hardness of ppm is obtained and can be equal to mg/L which is then recalculated to mmol/L to be converted to German degrees of hardness °dH, this is accomplished through the application of equations (1) and (2) as detailed by Mah (2023), along with equation (3) outlined by Bydén et al. (2003).

$$\frac{mol\ of X}{L} = \frac{\left(\frac{ppm\ or \left(\frac{mg}{l}\right)\ of X}{molweigth\ of X}\right)}{1000} \quad (1)$$

$$\frac{mmol}{L} = mol\ of\ X/L \times 1000 \quad (2)$$

1°dH ≈ 7.1 mg/L Ca and 1°dH ≈ 4.3 mg/L Mg (Svenskt Vatten, 2017), 1 °dH = 0.179 mmol/L (Bydén et al., 2003). To obtain the German degrees of hardness, equation (3) was used.

$$°dH = \frac{mmol/L}{0.179} \quad (3)$$

To calculate the water saving (WS) of RWH, equation (4) uses the volume of RWH expressed as m^3 (VHR) x% which is then multiplied by the water price (WP) in US$/$m^3$.

$$WS = (VHR \times X\%) \times WP \quad (4)$$

To calculate the environmental benefit (EB), equation (5) VHR x% multiplied by the environmental value of the water supply (VEB) in US$/$m^3$ is approximately 2.72 US$/$m^3$ with the 1994 monetary value (Costanza et al., 1998) and with the 2019 water supply.

$$EB = (VHR \times X\%) \times VEB \quad (5)$$

To obtain the Environment Benefit Cost-saving Potential (EBCP) for water in US$ with the value of today 2023, equation (6) is used and det total economic value (TEV), Table (4).

$$EBCP = \frac{(WS + EB)}{TEV} \times 2.02 \quad (6)$$

TEV for water supply in US$ 2019 the number was 1.70 US$/$m^3$ and fresh water 2.17 US$/$m^3$ (Cooley et al., 2019) while RWH was US$1 as calculated by Lancaster (2005).

A logarithmic mean and logarithmic standard deviation must be calculated, to perform a Monte-Carlo analysis (Colin & Erneland, 2023).

Statistics

To be able to describe the data obtained from the analysis of the rainwater samples and the sensor measurements, Excel was used. A more detailed description of the methods is found in Colin & Erneland (2023).

In the case of a diffusion of uncertainties for scant knowledge, Monte Carlo analysis was used. This method simulates the uncertainty numerically based on the n data entered in the simulation itself, which is then used randomly in the calculation.

Water Quality Index

By collecting limit values and guide values from several different references (Table 5) regarding the quality of drinking water, a Water Quality Index (WQI) was created, based on the parameters measured with the sensors. The scale on which WQI is based is described by three categories, e.g., whether the water is Serviceable (1), Serviceable with remarks (2) or Unserviceable (3).

Month	Temp (C°)	Precipitation (mm)	Sunshine hours (h)	i	PE	(P - PE)	R	ΔS / m²	ΔS*A (m³)
Jan	1.2	55.6	7.6	0.12	3.54	52.06	35.3	17	1195046
Feb	1.2	42.4	9.5	0.12	4.42	37.98	35.3	3	190800
Mar	3.3	40.9	11.75	0.54	15.84	25.06	15.7	9	667381
Apr	7.7	33.6	14.1	1.91	46.30	-12.70	15.7	-28	-2024900
May	12.3	41.1	16.2	3.86	87.02	-45.92	15.7	-62	-4393367
Jun	15.7	64	17.4	5.56	120.79	-56.79	18.7	-75	-5382140
Jul	18.2	62	16.85	6.94	136.61	-74.61	18.7	-93	-6653268
Aug	17.9	72.8	15	6.77	119.51	-46.71	18.7	-65	-4663671
Sep	14.2	55.9	12.75	4.79	79.64	-23.74	21.5	-45	-3225896
Oct	9.5	64.5	10.4	2.62	42.58	21.92	21.5	0	29605
Nov	5.5	59.5	8.25	1.15	19.02	40.48	21.5	19	1353085
Dec	2.6	65.8	7	0.37	7.35	58.45	35.3	23	1650922

Table 3. Data for Malmö, as well as calculations per month of the theoretical difference that occurs in the water reservoirs. P, PE, R, and ΔS are all in millimetres (mm). The grey column shows the total amount of storage by which the water reservoir, ΔS, has been multiplied by area A. The result is given in m3.

RESULTS

Below are the calculations made regarding quantity, quality, Environmental Benefit Cost-saving Potential, Statistical calculation, and simulation of the data with Monte Carlo analysis. Under the subheading Sensors, the calculated data is compared to the measured data from the sensors and the results obtained by these. The annual average global rainfall is 604 mm, and this value is the mean over three decades (Zeng et al., 2012). This means that the results in Malmö are above average precipitation globally (SMHI, 2023; OWID, 2023). By utilizing RHW, about 30-50% of the precipitation that falls can be taken out (Lancaster, 2005).

Sensors

The sensor value of measurement that was processed in the Monte Carlo analysis shows the RMV as within the 95^{th} %ile. The result was compared with the WQI. All sensor values were within the WQI except for turbidity.

$$WS=(VHR \times X\%) \times WP$$
$$4\ 425\ 550.8 = (5\ 086\ 840 \times 30\%) \times 2.90$$
$$EB=(VHR \times X\%) \times VEB$$
$$4\ 150\ 861.44 = (5\ 086\ 840 \times 30\%) \times 2.72$$
$$EBCP =((WS + EB))/TEV \ \times 2.02$$
$$324\ 353 = (8\ 576\ 412.2 / 1) \times 2.02$$

Table 4. The results in US$ from 2023, Malmö.

For the Monte Carlo analysis, only five of the six sensors were usable. The sixth sensor is the turbidity sensor, where WQI stands out (Table 2).

Table 6 is a combination of mean values derived from sample series of the low-cost sensors, and mean values from three laboratory measurements of rainwater in Malmö region. It is evident that the low-cost sensors display an overall higher value than found in the laboratory environment except for the pH values, which can be considered as equal.

Volume of rainwater

The quantity of rainwater in Malmö was calculated using Excel, based on data from Table 3. The research assumes that all runoff (R) reaches the reservoir. The result for the theoretical rainwater quantity can be calculated by multiplying water balance equation with the build-up and/or landscaped area for each region, as highlighted in grey in Table 3, equating to an approximate figure of $7.13 * 10^7$ m^2 (Colin & Erneland, 2023). Table 3 also describes the parameters based on an average spanning more than three decades for each month in the Malmö region.

Quality of rainwater

Water samples taken in Malmö have been analysed by an authorized laboratory (Debe AB in Hägersten). The parameters in Table 1, are used to monitor the

Very soft			Serviceable with remark			Unserviceable		
0 - 2	°dH	2	0 - 2 mS/m	Conductivity	2	0 - <4.5	pH	3
Soft			Serviceable			Serviceable with remark		
2 - 5	°dH	1	2 - 40 mS/m	Conductivity	1	4.5 - <6.5	pH	2
Medium hard			Serviceable with remark			Serviceable		
5 - 10	°dH	1	>40 - 250 mS/m	Conductivity	2	6.5 - 8.5	pH	1
Hard			Unserviceable			Serviceable with remark		
10 - 20	°dH	2	>250 mS/m	Conductivity	3	>8.5 - 10.5	pH	2
Very hard			WQI			Unserviceable		
>20	°dH	3				>10.5 -14	pH	3
Serviceable			Serviceable			Serviceable		
0 - <30 mg/l	Mg	1	20 - 60 mg/l	Ca	1	0 - 1.5 FNU	Turbidity	1
Serviceable with remark			Serviceable with remark			Serviceable with remark		
≥30 - 500 mg/l	Mg	2	≥60 - 150 mg/l	Ca	2	>1.5 - 3 FNU	Turbidity	2
Unserviceable			Unserviceable			Unserviceable		
>500 mg/l	Mg	3	>150 mg/l	Ca	3	>3 FNU	Turbidity	3

Table 5. Water Quality Index (WQI) for six different parameters that are used to determine water quality (LIVSFS 2022:12; Bydén et al., 2003; Svenskt Vatten 2010ab & 2013; WHO, 2017).

raw water and gives an indication of the water purity, the same parameters are used for raw water monitoring at waterworks.

Environmental Benefit Cost-saving Potential

The result in Table 4 from the evaluation of Environment Benefit Cost-saving Potential (EBCP) has been performed by calculating RWH in Malmö and this has been calculated with in Excel. The water saving (WS), and the Environmental Benefit (EB) have been calculated see Table 4. The input for the equations regarding Malmö has been taken from Table 3 for the volume of RWH in m^3 volume of rainwater harvesting (VHR). For total economic value (TEV), the value of RWH (1 US$), the %age is set to 30 % and Environmental value of the water supply (VEB) is set to 2.72. The average price of water in Sweden, denoted as WP, is US$ 2.90 per cubic meter (m^3). WS is calculated by taking the volume of RWH (m^3) from Malmö included as VHR in this calculation, multiplied by 30% which refer to lower outtake limit (Lancaster, 2005), which is then multiplied by WP per m^3 for Sweden in US$. EB is obtained by VHR multiplied by 30% and then multiplied by VEB. To get the result for EBCP, WS and EB are added and then divided by TEV. The sum is then multiplied by 2.02 to get the current value in US$. All results are presented in US$.

Monte Carlo analysis

The measurement series from the TDS sensor was calculated and presented according to the method Monte Carlo analysis. The dashed line shows RMV 35.75 ppm, where the value is found with a 95% probability. The Mean 14.88 ppm is found within the dashed box with a probability of 63.2% (Figure 3).

The measurement series from the TDS sensor was calculated with Excel, then the measurement series was converted to logarithmic values. Using these calculated values, a Monte Carlo analysis could be performed, and the values simulated 10,000 times. Then did the hardness °dH after that a Monte Carlo analysis has been run shows RMV (3.07), there is a 95% probability that the value will exist. The probable mean (1.28) with only a probability of 62.6%. The value of °dH was multiplied with 7.1 to get the value of Ca. A Monte Carlo analysis was performed, and the values were simulated 10,000 times. There is a 95% probability that the RMV is found 22.30 mg/l and Mean 9.12 mg/l and there is a 63.5% probability of finding the Mean. The value of °dH was multiplied with 4.3 to get the value of Mg. A Monte Carlo analysis was performed. RMV resulted in 13.49 mg/l, with a 95% probability. For the Mean, the value is 5.54 mg/l, with a 63.1% probability.

The measurement series from the Turbidity sensor was converted to logarithmic values. Using these calculated values, a Monte Carlo analysis was conducted. The dashed line shows RMV (.52), within that box there is a 95% probability that the value will exist. The probable mean (49.41) is found within the dashed box (Figure 4) with a probability of 61.2%.

The measurement series from the pH sensor was

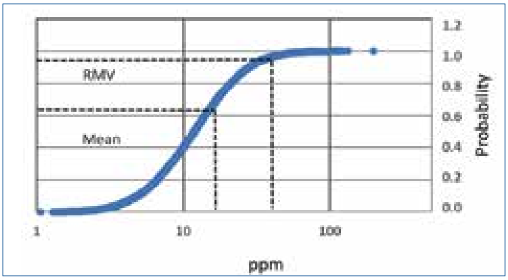

Figure 3. Shows the values for TDS in unit ppm that has been run by a Monte Carlo analysis (10,000).

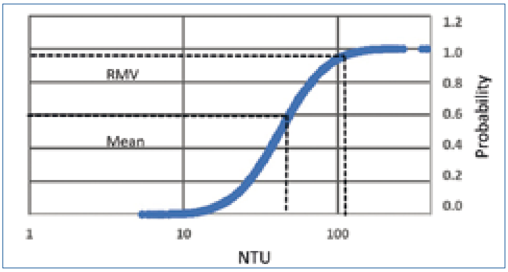

Figure 4. Turbidity run by a Monte Carlo analysis (10,000 simulations) and shown in the unit NTU.

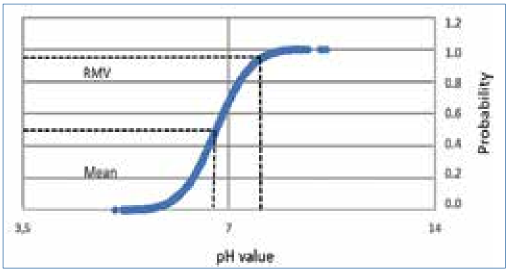

Figure 5. pH after a simulation of Monte Carlo analysis (10,000 simulations).

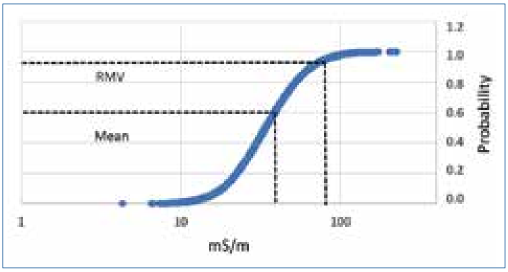

Figure 6. EC is shown in the unit mS/m after a simulation of a Monte Carlo analysis (10,000 simulations).

calculated by using Monte Carlo analysis. There is a 95% probability of finding RMV (7.84) within that box. The Mean (6.74) is found with 52.0% probability, within the box in Figure 5. The measurement series from the EC sensor was calculated and presented with the use of a Monte Carlo analysis method. The dashed line shows RMV 79.71 mS/m, which is located here, with a 95% probability. The Mean 38.86 mS/m is located within the dashed box, with a probability of 60.4% (Figure 6).

DISCUSSION

Water is becoming as valuable as oil and is unevenly distributed across the globe, leading to regional disparities in availability and quality. Climate change exacerbates these extremes, causing floods and droughts (IPCC, 2022). There are many reasons and advantages of RWH when compared with other alternatives such as desalination and wastewater purification. For example, it uses less energy and has less environmental impact when purifying drinking water. Moreover, it reduces flooding unlike the mentioned alternative. RWH has a clear head start as a complement (Yannopoulos et al., 2019).

Previous literature

The first peer-reviewed article on rainwater harvesting appeared in 1962, with a few contributions until 1999. However, since 2000, there's been an exponential increase in publications, with 2022 seeing a significant surge. The comprehensive review of existing literature on Rainwater Harvesting (RWH) indicates a significant evolution in the field since the turn of the millennium. Over the past two decades, there has been a notable shift in emphasis from quantifying rainwater to enhancing its quality. This transition points at the increasing reliance on advanced technologies, particularly in sensor technology. Modern sensors, with their increased precision, play a pivotal role in assessing water quality more effectively.

Moreover, the increase in global demand for water, driven by population growth, indicates the urgency of efficient water management practices. Amplifying this challenge is the impact of climate change on the hydrological cycle (Allan et al., 2020; Ahmadi et al., 2020; Straatsma, et al., 2020). Recent observations suggest a trend towards more pronounced climatic extremes. For instance, longer droughts, wildfires (Bergkvist, 2023), followed by intense rainfall, can overwhelm the soil's absorption capacity (Dahl, 2023). Such events exacerbate the adverse effects on urban infrastructure and ecosystems.

The Geographical area and the hydrological cycle

Geographically, Malmö experiences seasonal fluctuations in precipitation. In recent years, Sweden have had several flooding events, and Malmö is no exception, having flooded cellars to combat as well as land flooding and large amounts of supplemental water in the wastewater systems (Hernebring et al., 2015). During the summers of 2010 and 2011, the Copenhagen area, which is a neighbouring area to Malmö, was hit by three torrential downpours. During these downpours, the damage was so great that climate adaptation for downpour prevention measures was started immediately (Carlander, 2016).

The research looked at rainwater harvesting in Malmö, Sweden, finding that Malmö has considerable amounts of water to harvest (SMHI, 2023). The impact of climate change necessitates global data gathering to monitor changes and effects, such as floods and droughts (IPCC, 2022). In this study, laboratory measurements were conducted, and then compared with using low-cost sensors. This proved to be challenging, as one of the low-cost sensors did show some accuracy problems. The problematic sensor was the turbidity sensor, where the measurements displayed some outliers which were traced to calibration issues. The turbidity sensor calibration challenges are well documented by Trevathan & Schmidtke (2020). To overcome these problems, AI, machine learning and sensor fusion are seen as potential tools for enhancing sensor performance (Djenouri et al., 2022). Malmö's rainwater harvesting (RWH) was 1.526 * 10^6 m^3/year, calculated at 30% outtake, with potential savings of 17 million US$, though some measurement uncertainties were noted, particularly with the turbidity sensor. The quality parameters were found within the limit of serviceable water.

There are many examples of where potable water is used in applications that could utilize water of poorer quality, and that is not in alignment with sustainability principles. Moreover, the study looks at low-cost sensors, not from the perspective to enable complete understanding of the water quality, but to lower the cost of expensive water analysis in laboratory environments (Khamis et al., 2023; Silva et al., 2022).

Low-cost sensors and data analysis

The total cost for the sensors used in Malmö's local measurements was US$ 128 per cluster, with laboratory water analysis costing approximately US$ 90 per sample. The sensors enable frequent testing and the potential to reduce the number of tests required. As sensor technology advances, especially with artificial intelligence (AI), systems can learn to derive more detailed results from simple analysis methods. Zhang et al. (2021) have explored similar applications, such as using AI to remove tracking errors from car GPS systems, a principle that can be applied to other sensors, including those used in this study.

Monte Carlo analysis offers a more nuanced approach than simply relying on a "worst-case" scenario where all parameters are at their maximum. Instead of ending up with the extreme 100^{th} %ile, this study employs the Reasonable Maximum Value (RMV), which corresponds to the 95^{th} %ile. This provides a more conservative estimate, yet it remains practical and realistic. Through Monte Carlo analysis, numerous potential outcomes are simulated, which is unachievable by deterministic models (Öberg, 2009). This method is a powerful way to describe uncertainty and variability. Monte Carlo is well suited when there is empirical data in the form of a series of measurements, thus the method has been used in this investigation to simulate the measured input from the sensors values 10,000 times.

Developing a WQI

Water quality was categorized into three levels using a matrix, with indexes 1-3 representing serviceable, serviceable with remarks, and unserviceable water, respectively. Challenges with low-cost sensors were clear, particularly in turbidity measurements, where calibration issues resulted in inconsistent values. High readings were contradicted by clear water appearance, and further analysis revealed that the sensor was noisy below 100 NTU (Trevathan et al., 2020). More advanced turbidity meters ranging from US$ 200-800 are recommended as a solution. An instance of cross-contamination from the sensor data was identified and removed from the data, collected on March 22 and 23, 2023.

The sensors used a 5 V reference voltage, but the 12-bit ADC input pins could only handle 0-3.0 V, forcing the study to use a 3.3 V output instead. This discrepancy may partially explain the higher values compared to laboratory results, and further investigation is needed. A notable difference between low-cost sensor data (mean value in Table 6) and single-point laboratory measurements also exists.

MEAN VALUE	°dH	Ca	Mg	Turb	pH	EC
Lab Malmö	0.25	1.30	0.28	1.25	6.63	3.27
Sensors Malmö	1.28	9.11	5.55	49.71	6.75	39.07
Different Sensors and Lab	>5.12	>7.00	>19.82	>39.77	Equal	>11.95

Table 6. Comparison between mean values from laboratory and the low-cost sensor data.

The pH of the water was relatively consistent, though some variations were observed. In areas like West Kalimantan, Indonesia, rainwater acidity is affected by factors like rooftop material (Khayan et al., 2019), where the pH ranged from 4.78 to 5.58, shifted toward a more acidic level compared to this study. Additionally, Khayan et al. (2019) reported that rainwater encountering a tin roof had an average turbidity of 20.0 NTU which is reduced to 5.67 NTU after treatment.

Environmental Cost Data

The biosphere's economic value is estimated to be US$ 16-54 trillion annually, averaging US$ 33 trillion — which is almost double the global GDP of US$18 trillion. The 1994 valuation of the water supply, adjusted for inflation, is approximately US$ 1,692 * 10^9 multiplied by 2.02 (Measuring Worth, 2023). By 2050, water demand is projected to reach 5,500 km^3 to 6,000 km^3, possibly depleting many aquifers and contributing to salt contamination of the coastal aquifers with salt. Our current consumption rate is close to unsustainable (Boretti & Rosa, 2019) with global outlet use rising 1% yearly since the 1980s (UNESCO, 2022). The global daily consumption of virtual water averages five m^3/person (Sydvatten, 2020), and this might need to reduce by 20-30% by 2050 (World Economic Forum, 2019). Water in Sweden costs 2.90 US$/$m^3$ (World Bank, 2022), and up to 50% of RHW's precipitation can be utilized (Lancaster, 2005). In 2016, settlements covered 5.95 * km^2 of the Earth's 150 * 10^6 km^2 land area (World Economic Forum, 2021).

In 2020, U.S. companies reported a US$ 301 billion economic impact related to water risks, which is five times greater than prevention costs at US$ 55 billion (CDP, 2023). Globally, water-related economic losses could reach US$ 500 billion annually (UN Water, 2021).

CONCLUSION

The present paper describes how RWH can ease the pressure on the general water supply in Malmö, Sweden. The precipitation can be collected on hard surfaces such as roof tops. The potential of RWH in Malmö is 1.526 * 10^6 m^3/year.

The study reached several conclusions:

- Simple sensors might be used to get a reasonable understanding of the rainwater quality, and with that, less laboratory testing is needed, lowering the cost for testing of the rainwater. Results from the pH-, TDS-, and EC sensors showed that the data was regarded as useful.
- A Water Quality Index (WQI) could be established based on six crucial parameters: °dH, Mg, conductivity, Ca, pH, and turbidity.
- With the measurements from the low-cost sensors, some of the laboratory measurements could be reduced, and thereby lowering the cost for the water quality measurements. The low-cost sensors also provide the basis for continuous monitoring of the water quality.
- Laboratory results suggest that harvested rai water could replace the water in Malmö for flus ing toilets and similar applications, thus decreasing the pressure on the conventional water supply infrastructure.

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