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Title

Sustainable water resources through harvesting rainwater and the effectiveness of a low-cost water treatment

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Abstract

Increases in world population and climate change are some of the pressures affecting water resources for current and future water availability. The variability in water availability can reduce agricultural yields, food supplies and potentially leads to malnutrition and spread of diseases in water-poor countries. Even some water-rich countries can experience prolonged periods of dry weather, causing a drop in water reservoirs levels, forcing more restricted water resources management. Rainwater harvesting is one key option in adapting to water shortage and future demands that may alleviate the pressure on existing water resources. This work evaluates a roof top rainwater harvesting system (RWHS) installed as part of a decentralised wastewater treatment system designed to enable a circular economy by providing a more reliable water supply system in a remote public school in rural India. The effectiveness of the RWHS in reducing the pressure on a groundwater supply was assessed along with the physical, chemical and microbial characteristics of the stored rainwater over time. Further, the application of a low-cost primary treatment to make the harvested water safe to use for multiple purposes was investigated. The results revealed that the harvested water was of acceptable quality at the start of collection, however, microbial abundance increased when the rainwater was stored for a long time without treatment. Thus, a chlorine dosing regimen for the RWHS was designed based on laboratory and field experiments. The results also demonstrated that the low-cost chlorination process was effective in the field in reducing microbial abundance in the stored water for more than 30 days. However, as the residual chlorine level was reduced with time to <0.2 mg/l in the storage vessel, the microbial abundance increased, albeit to a much lower level that meets the Indian bathing water standards. The results provide evidence that installed RWHS has reduced the pressure on existing water supply at the school by up to 25% of the water that used for washing and flushing with no treatment, and with regular chlorination, greater savings and multiple uses of the stored rainwater can be achieved.

Key words: Water management, harvested rainwater, water treatment, sodium hypochlorite.

1. Introduction

Increases in world population and climate change are some of the pressures affecting the availability of water resources. According to the United Nation projections, the world population is predicted to increase from 7.8 billion people at present to a further 2 billion people by the end of the century (UN, 2019). China and India remain the two most populous countries with 19 and 18% of the total global population, respectively (UN, 2017). This predicted population increase poses stress on food and water resources on both local and global levels. Water resources and food security are highly dependent on climate (Rosenzweig et al., 2001; Misra, 2014; Myers, 2017) with climate change is predicted to have a negative impact on food supply and crop yield as the demand for water for irrigation is increased and water resources are decreased (UN, 2018). It is also predicted that climate change is most likely to increase the variability of precipitation, flood and drought episodes (Solomon et al., 2007; Trenberth, 2011; Vinod and Lopez, 2015). These variations in meteorological conditions and the increase in storm events can affect soil conditions, water availability and agricultural yields that could potentially lead to the reduction in food supplies, malnutrition and spread of diseases in some of the world's poorest countries (Rosenzweig et al., 2001; UN, 2018; Tabari, 2020).

Climate change and water shortage can also affect the water level in water-rich countries. For example, in the UK, there is usually sufficient water to meet human needs except during prolonged periods of dry weather as the water level in reservoirs drops. However, in recent years, water shortage has regularly occurred in England and Wales which, coupled with population increase warrants that water resources to be managed carefully during those dry periods (Caraballo et al., 2016; Environment Agency, UK, 2018; Saatsaz, 2019). Introducing water meters instead of a fixed water rate and imposing hosepipe bans are some of the measures used during prolonged droughts in the UK. In the USA, Australia and Europe, water resources are also under greater stress, particularly in drier countries such as Spain, Italy, Greece, Cyprus and Malta (Mancosu et al., 2015).

As a response to water shortage, groundwater has been increasingly exploited to meet water demands in Asia (India, China, Iran,) and many counties in Africa (Xu and Usher, 2006; Misra, 2014) as the main source of water for drinking, cooking, sanitation and irrigation. The World Bank (2012) stated that India alone uses 230 km^3 of groundwater per year and >60% of the extracted groundwater is used for irrigation (Siebert et al., 2010). As a result, groundwater sources in many countries including India are deteriorating due to over-pumping and pollution (Scott and Suhag, 2004; Panda, 2011; Pophare et al., 2014). It is reported that the majority of India faces critical drought conditions and water shortage (NASA, 2019), and approximately, 65% of India's reservoirs are running dry as a result of low rainfall and inadequate water management. Moreover, The Indian National Commission for

Integrated Water Resource Development stated that the total availability of water in the country is lower than the projected demand and water requirement by 2050 (NITI Aayog, 2018). Therefore, adopting a water management system to meet current and future water demands is a critical issue. Rainwater harvesting can be considered as one key option to alleviate the pressure on groundwater and to ensure a sustainable future for water resources management (Rahaman et al., 2019).

In rural India, the government water supply is 55 L/person/day (India Water Factsheet, 2019), which does not take into account livestock needs. Whereas government water supply to Indian towns and cities varies from 70-150 L/person/day. Approximately >50% of this amount of water is not used for drinking, which means that water that has been physically, chemically and biologically treated in Water Treatment Plants, is flushed down the toilet or the drain. Collecting and utilizing wasted rainwater that otherwise would flow down the gutter and into the drains not only can play a key role in water security but also, it may reduce the risks of flooding (Domènech and Sauri, 2011; Freni and Liuzzo, 2019) as the water overflows into a soakaway, reducing the stress of public storm drains.

A typical rainwater harvesting system operates where precipitation falls onto a surface (roof, floor or trenches) and is collected through gutters and transferred through a network of pipes to a storage container. The captured rainwater is typically reused locally in homes and gardens for many purposes, thereby improving the sustainability of water resources. Rainwater harvesting has been practiced in India for centuries, however, many traditional rainwater harvesting systems have fallen into disrepair for many reasons including their inability to meet the community's needs (Kumar et al., 2006) while the reliance on groundwater is increased (Van Meter et al., 2014). In recent years, rainwater harvesting is encouraged throughout India and is used to recharge wells, borewells as well as to replenish underground aquifers (Stout et al., 2017).

The focus of this work is on rainwater that is collected as a roof runoff, for it is considered to be relatively cleaner than that collected from other surfaces. However, roof runoff can contain a large concentration of metals, nutrients and other pollutants (Melidis et al., 2007) acquired through precipitation, atmospheric deposition and from the material used to construct the roof. As rain droplets descend through the atmosphere, they dissolve gases, absorb aerosols and collect suspended particulates of dust and ash (Huston et al., 2009) that contaminate otherwise clean water. For example, acid rain is the product of rainwater absorbing sulphur and nitrogen from the atmosphere where the main sources are vehicles' exhaust fumes, fossil fuels burning, industries and other anthropogenic and natural processes, which cause pH reduction of rainwater in regions with high industrial and traffic volumes (Melidis et al., 2007; Lee et al., 2010). Roof runoff also may contain bacteria from bird and animal droppings, which can contaminate the harvested rainwater. For these reasons, in many developed countries including USA, Japan, France and the UK, rainwater is not recommended for drinking and its uses are limited to flushing toilets, washing pavements and irrigation (Lupia and Pulighe, 2015; Vialle et al., 2015). However, in many developing countries where water is scarce, rainwater is used for both potable and non-potable uses posing risks to human health (Silva et al., 2015). Thus, it is important to understand contaminants behaviour and their interactions after collection and during storage in order to implement the necessary measures to improve the quality of the harvested rainwater.

In this work, a roof runoff rainwater harvesting system was introduced as part of a wider decentralised wastewater treatment system (DWWTS) in a school in rural India that aimed to improve water access as a response to water scarcity and associated inadequate sanitation issues. The DWWTS comprised of a rainwater harvesting system, a greywater treatment and recycle system (Subramanian et al., 2020), a blackwater treatment system including new toilets, septic tank systems and a constructed wetland for the treatment of wastewater. Prior to the implementation of the DWWTS, wastewater effluent from the school was directed through open drains and discharged into a nearby lake risking contamination of groundwater sources, spread of disease and polluting the environment. The school is in a remote location and is dependent on the unreliable village water supply that is sourced from groundwater. The harvested rainwater (HRW) was therefore intended to supplement the existing water supply system available to the school and to irrigate the constructed wetland, built as part of the DWWTS, during the school holidays and in dry periods. The purpose of the constructed wetland is to treat and polish the septic tank effluent before discharge to the environment, and thus, the wetland's vegetation requires hydration all year round. We report the method used to collect and store a large quantity of rainwater (Xm^3) in the small area provided for the rainwater harvesting system designed to provide water for non-potable use. Further, we report the effectiveness of chlorination as a simple low-cost and low energy water treatment that can be applied to the stored water to improve its quality, and thereby increase the range of possible uses of the collected rainwater. The hypothesis is that the HRW may reduce the pressure on groundwater supply and we further hypothesise that intermittent in-tank chlorination could effectively reduce the growth of the microbial population in the stored rainwater to produce water with reasonable quality at minimum running cost.

2. Materials and methods

2.1 Site description

The school is located in the small village of Berambadi in Chamarajanagar district in Karnataka, India (Supplementary material, Figure S1) which has an average annual rainfall of 915 mm/year during the monsoon season from May to mid-December (Karnataka State Natural Disaster Monitoring Centre, 2020). The school serves >200 students (age ranged from 5-15 years and the gender is split, 50% female and 50% male). The source of water for the school is borewell water (groundwater), which is a common source of drinking water in the village. Prior to the installation of the DWWTS, for many reasons including water shortage, deteriorating groundwater quality, power failure, intermittent village water supply delivery and water leakage, there was often no running water available in the sanitation outlets in the school with female students, in particular at a greater disadvantage.

2.2 Estimating water demand for the school

Prior to the construction of the DWWTS, four flow meters were installed to the plumbing lines in the school (two supplying hand washbasins, one supplying the kitchen and one supplying the existing toilet block) in order to measure the baseline daily water use. Data from the flow meters averaged over 4 weeks determined a daily water usage for the school at 2000-2500 L/day distributed between hand wash, kitchen, and the toilets including leakage from existing damaged water pipes. The blackwater generated from this system was estimated from the flow meter installed to the existing toilet block as 800-1000 L/day including the leakage from damaged pipes. To estimate the annual water demand for the school, average daily water use was multiplied by the number of school academic days of 231 to give an annual water demand of 462,000-577,000 L/year. Due to financial and special constraints on site, the RWH installed was not aimed to be the only source of water provision to the school, rather it was intended to supplement (not to replace) the existing regime of village water supply. Thus, the system was designed in relation to the collection area of the best available pre-existing rainwater catchment surface (2 classroom roofs) at the school and the size of the water storage vessel designed accordingly.

2.3 Rainwater roof catchment area

Rainwater collection area or water catchment surface, in most cases, is the roof of a house or a building that catches raindrops and channels them to a collection gutter, which in turns directs the rainwater to a network of pipes leading to a storage vessel. In this work, two existing classroom roofs were utilized for receiving rainwater (Figure S2). The size of the available roof catchment area and the average annual rainfall determine the maximum possible volume of rainwater that can be harvested, which is calculated using equation 1 (Rational Method, 2014):

$$\textbf{The quantity of rainwater to harvest} = \mathbf{A \times R \times \mathit{RC}} \qquad (1)$$

Where A is the roof surface area designated for rain catchment (m^2), R is the average annual rainfall (mm/year) and *RC* is the runoff coefficient. The runoff coefficient of 0.70-0.95 for any catchment surface and is the ratio of the volume of water that runs off the surface to the volume of rainfall that falls on the surface (Farreny et al., 2011), which varies with the slope of the roof and the roof material (concrete, corrugated metal sheets, plastic, tiles and corrugated plastic). For example, *RC* of 0.75 means that approximately 75% of the rainwater would be collected with an estimated loss of 25% by splashback, evaporation, wind and overflow of gutters.

The two existing concrete classroom roofs (Figure S2) were prepared to receive rainwater with a total catchment area of 111.48 m^2, average annual rainfall (2017-2018) of 915 mm (for Karnataka region) and runoff coefficient of 0.75-0.95. Therefore, the collection potential of the system was estimated to be76,000-96,000 L/year of rainwater.

The roofs were cleaned, washed and painted with a layer of a nontoxic and durable water-proofing paint (Brushbond RFX), which was sourced locally. The surfaces of the existing roofs had very shallow slopes, which were tilted towards one side to allow the collected rainwater to drain towards the outlet plumbing. The outlet plumbing was protected by a metal mesh surface to exclude leaves and debris from entering the rainwater plumbing system.

2.4 Rainwater transport system

The collected rainwater was transported by gravity via 4 inches polyvinyl chloride (PVC) pipes and downpipes to a first flush component to discard of the first few mm of rainwater to the drains, ensuring that any sediments or debris that may be still present on the roofs are eliminated and washed to drains. After the first flush, a valve is manually opened to allow rainwater to flow to a metal water filter system before reaching a storage vessel. The filter operates on gravitational force, has a mesh size of 250 microns, with a capacity of 105 L/min and designed to filter out small debris transferred with the rainwater (Figure S3). The filter material is rust-proof with an inbuilt self-cleaning mechanism and was sourced locally. The filtered rainwater was then channelled by gravity to a storage vessel and can be transported to the point of use through valves and pumps as illustrated in Figure S6.

2.5 Storage vessel

Due to lack of space in the school ground to accommodate a large water storage vessel, it was decided that an underground sump would provide a better use of the space. Thus, a void was dug in the ground and a concrete foundation was built to support a reinforced concrete sump with dimensions of 5m x 6m x 2.5m with a supporting wall in the middle. The sump has the capacity to contain 58,000 L of rainwater and was internally painted with a nontoxic water-proof layer (Dr. Fixit Dampguard), which was sourced locally, and the tank was tested for any water leakage. It is noted that the storage volume of the tank is much lower than the estimated rainwater collection potential of the roof however the storage volume was dictated by cost and space constraints. A water level indicator was installed inside the tank for measuring the stored water level as and when required. The roof of the sump had four openings (one at each corner), each of which had a tightly fitted cover (Figure S4). The covers were securely locked at all times except during inspection, reading water volume and cleaning processes. A plumbing system and a pump were installed for pumping and transporting the stored rainwater to potential points of use, which would be dependent on the quality of the HRW.

2.6 The quality of harvested rainwater

In the first few months of operating the RWHS, 33,000 L of rainwater was collected and stored in the sump. For the purpose of comparison, stored rainwater and mains water (groundwater) were sampled and tested every two weeks to monitor microbial, chemical and physical water quality over time. A number of water quality indicator tests were conducted on the rainwater and groundwater in the field, including pH and electrical conductivity (EC) using YSI pro1030, Yellow springs, USA; turbidity using Systronics Digital Nephelo-Turbidity meter 132, Systronics Ltd, India. Other parameters were determined in the laboratory by Ashoka Trust for Research in Ecology and the Environment (ATREE) including alkalinity by titration method, biological oxygen demand (BOD) by azide-modification titrimetric method and suspended solids (SS) that was determined gravimetrically. Chemical parameters such as total phosphorus (TP), soluble reactive P (SRP), total nitrogen (TN), nitrate (NO_3-N) and total organic carbon (TOC) were determined using Spectroquant Prove Spectrophotometer 600, Merck KGaA, Germany. The concentration of selected metals was measured using atomic absorption spectroscopy (AAS). Microbial indicators including total coliforms and *e. coli* were determined using Colilert-18/ Quanti-Tray 2000 (IDEXX, Maine, USA) and following the manufacturer's instructions. As a control, the village water supplied from a borewell to the school was also analysed. All the analyses were conducted in triplicates and analysed within 24h from collection time.

2.7 Water treatment

Rainwater is considered cleaner than the surface and ground waters (Khayan et al., 2019; Rahman et al., 2019), however, to prevent the growth of bacteria during the storage period and to make the water safer to use, a form of treatment or disinfection was required. For this study, a low level of disinfection was preferred as the wastewater resulting from the use of the HRW would eventually be discharged to the constructed wetland designed for wastewater treatment, in which high levels of residual chlorine might have inhibited biological treatment. Chlorination with sodium hypochlorite liquid (4% strength) was the chosen disinfection method for this work, for its availability and relatively low cost. To decide the lowest required amount of disinfectant for the volume of the collected water, an initial laboratory experiment was conducted to determine chlorine demand and thus the chlorine dosage required to maintain a safe level of residual chlorine.

2.7.1 Determination of chlorine demand and chlorine residue

A laboratory experiment on the HRW was conducted in order to determine chlorine demand of the stored rainwater. Eleven volumetric flasks (100 ml capacity) were filled with 99 ml of well-mixed rainwater from the sump. Each of these flasks was dosed with 1 ml of chlorine solution with concentration from 5 to 50 mg/l of chlorine that was prepared from 4% sodium hypochlorite liquid (Qualigens, Fisher Scientific) and a blank (not dosed with chlorine). The flasks were mixed well to give a final concentration from 0.5 to 5 mg/l of chlorine. The flasks were covered with foil paper and allowed to stand in the dark before testing for residual chlorine after 1, 2, 3 and 5h, using Spectroquant Picco chlorine testing photometer, Merck KGaA, Germany. Residual chlorine of each flask was determined in mg/l, following the manufacturer's instructions.

Chlorine demand of the HRW, which is the amount of chlorine consumed by reaction with organics, bacteria and metals that are present in the HRW, was calculated by subtracting the measured residual chlorine from the concentration of chlorine that was added to each flask (mg/l). From this information, the appropriate chlorine dosage was calculated as equation 2:

Chlorine dosage (mg/l) = chlorine demand (mg/l) + residual chlorine (mg/l) (2)

The appropriate chlorine dosage that produced residual chlorine of ≤ 1 mg/l after 5h of contact time was chosen for chlorine dosage trial. This laboratory experiment determining chlorine demand, residual chlorine and chlorine dosage were repeated again in the following rainy season for the freshly HRW for the second year of operation.

2.7.2 Chlorine dosage trial

The calculated chlorine dosage was then applied to a small volume of the stored rainwater to monitor residual chlorine consumption over 24h. A triplicate of 1 litre clean glass bottles were filled with the HRW samples and dosed with chlorine to give 1.55 mg/l calculated according to section 2.7.1. A blank was included for control. The bottles were covered with foil paper to prevent light exposure and left at room temperature. To monitor residual chlorine decline with time, the samples were tested for residual chlorine at 1h time intervals from 1h to 6h and after 24 h using Spectroquant Picco chlorine testing photometer, Merck KGaA, Germany. After the 24 h, water quality indicator tests were conducted on the dosed rainwater including total coliforms and *e. coli*. This process was repeated again in the following rainy season for the newly collected rainwater.

2.7.3 Application of water treatment on a large scale in the field

Four rainwater samples were collected, one from each opening of the sump for water quality indicator tests to mark the baseline before chlorination. Chlorine dosage was scaled up and applied in the form of sodium hypochlorite (4% strength) to the volume of stored rainwater in the sump of approximately 33000 L. The appropriate volume of sodium hypochlorite was diluted in a clean bucket of rainwater collected from the sump and poured back at each of the four openings of the sump and mixed well with a clean plastic oar. Residual chlorine was then tested from each opening on an hourly basis for 5h and after 24h of contact time. After 24h contact time, the treated rainwater samples were collected for water quality indicators to mark the after-chlorination water quality. Before and after chlorination samples results were compared. The treated rainwater in the sump was monitored for quality fortnightly over a longer period of time. This process of water treatment by chlorination was repeated in the following rainy season for the freshly HRW.

3. Results and discussion

In this work, a rainwater harvesting system was installed in a public school in a rural village in India to ensure a constant supply of running water to the school, as a part of decentralised wastewater treatment system. Long term precipitation data for the region indicated that the mean annual rainfall is 900-1000 mm (Environmental Research Observatory M-TROPICS, 2020), however, the monthly precipitation level is irregular throughout the year with the bulk of these rain is limited to May – October) with peak precipitation during the month of August (Supplementary material, Figure S5). This suggests that water can be scarce and the pressure on water resources for the rest of the year is high. The lack of regular running water often results in poor sanitation, health deterioration and frequent missed education (UN, 2020). Implementing an adequate rainwater harvesting system is therefore essential to support and supplement the existing water supply system to the school.

The harvested rainwater may hold some challenges of its own such as the build-up of sediments, algae, bacteria and pathogens deposited on water catchment surface by birds, insects and rodents (Evans et al., 2007). Despite that, rainwater is often considered a cleaner source of water, which can be more suitable for drinking than surface water (Khayan et al., 2019; Alim et al., 2020). This assumption is primarily due to having fewer contaminants than surface or groundwater. Nevertheless, water is essentially a solvent and when it hits an unclean surface or polluted air; it picks up many contaminants and becomes polluted with microbes, chemicals and sediments. However, the higher level of contamination is expected to be found in the first flush of rainwater, which was prevented from entering the storage vessel by discarding it to drains and generally contaminants are reduced as the rainfall continues (Hofman-Caris et al., 2019).

The HRW in this work was monitored over time to determine its quality and changes in characteristics during the storage period and to compare HRW with the currently available drinking water (groundwater). The primary concern was the presence and the accumulation of bacteria in the stored rainwater with time (Figure 1). Figure 1 revealed that during the initial observation period that the microbial water quality degraded over time as predicted. However, during the period Dec-Jan, the water quality appeared to improve over time. As this was unexpected, the local system operator was consulted to determine any irregularities in operation during this period revealing that the rainwater in the sump was supplemented with village water at some points from December to February. However, the addition of village water to the HRW did not affect the flow of this work, as it would be a common practice for the school to supplement the sump water with excess village water. Subsequent to the cessation of groundwater to the system, a rise in bacterial concentration was again observed as had been anticipated. Thus, confirming the importance of applying some treatment to HRW before use.

There are a number of methods of water disinfection available, and this current work required a simple, low cost and practical type of disinfection with limited running costs and inherently safe process that may require to be carried out by unskilled labour. Chlorination is effective against harmful bacteria as it destroys the membrane of microorganisms upon direct contact (TECQ, 2007). As the intended uses of the harvested water in this work was irrigation, washing and flushing only, not for drinking, thus a combination of filtration and chlorination at frequent intervals could be sufficient to prevent sediment and microbial built up in the water storage sump. Therefore, disinfection with sodium hypochlorite liquid was chosen for its availability, relatively low cost and ease of use to disinfect the HRW.

The disinfection of rainwater in the laboratory under controlled conditions indicated a chlorine demand value of 0.99 mg/l, which is the amount of chlorine that reacted with organics, bacteria and metals present in this harvested water. To achieve effective disinfection, the addition of sufficient amount of chlorine was applied to give free chlorine residue of at least 0.3-0.8 mg/l to continue to disinfect the water during its residence time (WHO, 2003; SDWF, 2020). Our laboratory trials determined that a chlorine dosage at an initial concentration of 1.55 mg/l resulted in residual chlorine level of 0.56 mg/l after 24h of contact time (Figure 2a). The reduction in chlorine level from 1.55 mg/l to 0.56 mg/l is an indication of chlorine consumption during the chemical reaction with contaminants present in the water. Although higher residual chlorine up to 4 mg/l in drinking water poses no health risk to human and is considered acceptable by the Environmental Agencies (Wiant, 2010), for this work, it was crucial to limit the level of chlorine in the treated water as one of the intended water uses was to irrigate a constructed wetland designed for treating black water wastes during the school breaks. Therefore, it was essential that chlorine level in the treated water does not pose any chemical or biological threat to the receiving constructed wetland biota, and hence, the lowest possible residual chlorine level was required during water treatment.

A variation in chlorine demand and residual chlorine was observed when chlorine dosage was scaled up and applied to the volume of rainwater stored in the sump of approximately 30,000L. The sump water showed a higher chlorine demand (1.36 mg/l) than the laboratory-controlled work (0.99 mg/l) and the residual chlorine level after 24h in the field was lower (0.34 mg/l) than that determined in the supporting laboratory experiment (0.56 mg/l). This discrepancy was likely due to the differences in the controlled conditions and the reality of the challenges in the fieldwork. For example, the sump water may have higher organic loading and more sediment than the water sample collected due to variable water quality arising from uncontrolled environmental conditions. Whilst so, the residual chlorine in the field was within the acceptable level (0.2-0.5 mg/l) proposed by the WHO (2003) for drinking water (Figure 2b). Thus, it was assumed that the residual chlorine in the water would continue to disinfect the water during its residence time in the sump until it reached the point of use.

The application of chlorine to the sump water resulted in a 100% reduction of microbial abundance (Figure 3a) and BOD indicating the effectiveness of chlorination process in producing more safe water to use. However, within 3 weeks of chlorine application, water quality monitoring data indicated an increase in bacterial and BOD concentrations, and by 4-6 weeks, their levels were similar to that before the treatment. This is because the residual chlorine that was left in the sump water was gradually consumed over time by contaminants inside the sump to a non-effective level (Figure 3b). As a result, the stored HRW was used for plant irrigation only.

In the subsequent collection of rainwater and chlorination events, 45,000 L of rainwater was harvested in the sump, which is termed harvested rainwater 2 (HRW2). The chlorine demand for HRW2 was 0.86 mg/l and the rainwater dosed with 2.5 mg/l of chlorine on two separate occasions, which gave residual chlorine of 1.71 mg/l after 3 h of contact time and dropped to 0.64 mg/l after 24h of contact time. Multiple chlorination events were necessary to prevent microbial growth which was inversely correlated with residual chlorine level in the water sump (Figure 4). After the multiple chlorination events, microbial population in the sump water was reduced by 100%, but regrowth occurred within 37 days of the treatment to 17 MPN/100 ml, which coincided with residual chlorine of <0.2 mg/l. This suggested that chlorine decay in the stored water system was > 30 days. Meantime, groundwater mains supply to the school, which designed for human consumption had an average microbial abundance of 849 MPN/100 ml for the same period of time (October to December). This suggests that the treatment of the stored rainwater produced a better-quality water than groundwater mains supply (Table 1). It is worth noting that in a typical operational system, the HRW would be used as and when it is collected, which will reduce microbial growth as freshwater is frequently supplementing the sump water. This study highlighted that the stored treated rainwater should be used within 37 days and to maintain a high quality of the stored water, repeated chlorination at regular intervals is necessary.

Collecting rainwater that otherwise is wasted or directed to drains and use it in times when the water is scarce is a logical and desirable concept (Kulkarni et al., 2015; Chindarkar and Grafton, 2019). In this work, when the collected rainwater is used for washing hands, cleaning floors and irrigating the constructed wetland, a saving of 800-1000 L/day (equivalent to 25% of the school water allocated for washing and flushing the toilets) of mains water supply occurs. Nonetheless, the quality of the rainwater is important and depends on factors such as rainfall intensity, the nature of rainwater harvesting system, the maintenance of the rainwater catchment area and the storage tank (Lee et al., 2010). This study revealed that HRW meets the Indian bathing water standards (CPCB, 2009) even without treatment for pH, EC, turbidity, alkalinity, total hardness, nitrate, BOD and DO (Table 1). Moreover, for total coliform, HRW meets the bathing water standards when used within 3 months of collection without treatment (Figure 1). This work also revealed that with simple disinfection method, the HRW can meet the Indian drinking water standards (CPCB, 2009).

In rural areas such as the location of the school in this study, it is expected that rainwater would be relatively free of atmospheric pollutants and metals as indicated from the results and compared to the quality of current drinking water system supplied to the school, which is sourced from groundwater (Table 1). Electrical conductivity, alkalinity and total hardness of groundwater are statistically significantly elevated $p<0.05$ than HRW. Alkalinity in the untreated and treated harvested water (97 and 63 mg/l, respectively) is within the level recommended by environmental agencies in many countries (Wilson, 2019), while the alkalinity of groundwater of 234 mg/l, which is influenced by the geology of the source and indicates the presence of carbonate and hydroxyl anions in the water (Wilson, 2019), is much elevated beyond the recommended range of 80-120 mg/l (Safe Drinking Water Foundation SDWF, 2017; Mechenich and Andrews, 2004). Metal concentrations were also typically less in HRW than in drinking water. For example, manganese (Mn) level was significantly lower $p<0.05$ in HRW, while copper (Cu) concentration was comparable to that of the current drinking water supplied.

Surprisingly, drinking water in this study, which is sourced from groundwater contained considerable levels of coliforms bacteria that ranged from 33 to >7000 MPN/100 ml and averaged at 1552 MPN/100 ml throughout the monitoring period of this work. The presence of coliforms bacteria in the groundwater supply to the school suggests either water contamination during its transport from source via pipelines to the school, or, low groundwater quality at source in the region of the study (CPCB, 2011) and as is apparent in many regions dependent heavily on groundwater supply (Sekhar et al., 2016). In contrast, during rainwater treatment periods, the level of coliform was reduced to <1 MPN/100 ml in HRW, highlighting the effectiveness of water chlorination process. To increase the effectiveness of the disinfection process, regular application coupled with routine testing for residual chlorine is recommended to ensure maintenance of an acceptable chlorine residual and thereby provision of continual disinfection during the storage period.

For the stored untreated HRW, the level of coliform was greater than in groundwater supply (Table 1), and therefore, deemed unsuitable for potable use. Even so, if the purpose of the HRW is not for drinking, and if the collected rainwater is used without lengthy storage periods the system here could potentially save >1000 L/day of water that would have otherwise been drawn from the regular water supply. In balance, this work highlighted that chlorination of rainwater can improve the quality of the stored water, and regular application of sodium hypochlorite is required at regular intervals. We propose that further study would be beneficial to determine whether supplementary treatment is necessary, such as ozonation or UV lamp exposure before and at the point of use, in order to ensure the water is suitable for potable use. Overall, the system studied may be considered a low-cost and effective method for rainwater collection and treatment demonstrably reducing the pressure on groundwater resources. The system can be readily replicated in many different settings in rural areas of many countries and can be a simple or a more elaborate system to suit the needs of all users in water-deprived regions.

4. Conclusion

Rainwater harvesting is a viable mean in reducing the pressure on surface and groundwater resources and may provide a solution to water shortage in many rural communities as an additional source of water supply. Rainwater harvesting system was installed in a public school in rural India to supplement the existing water supply system ensuring a regular flow of running water is available. This study demonstrated that rainwater that otherwise is lost to drains may save equivalent to 25% of the water used for non-potable purposes, that could offer a way to aid health and sanitation issues in rural communities.

The results revealed that HRW meets bathing water standards in India even without any treatment. However, storage of water for more than 3 months, create an increase in microbial activity and a simple and low-cost disinfection method was required. Chlorination with sodium hypochlorite was applied to the stored rainwater based on laboratory experiments to determine chlorine demand, chlorine residue and dosage required for the disinfection. In the system studied, chlorination was effective in reducing microbial count, biological oxygen demand and produced water with better quality that met drinking water standards in India. In this system, the effect of chlorination was maintained for 30-37 days suggesting multiple application of chlorine was required. This work highlighted that a simple and low-cost method of disinfection can be applied to HRW, and chlorination is a dynamic process, which requires an additional treatment before or at the point of water use. Conversely, chlorination may not be necessary if the stored rainwater was intended for non-potable uses.

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Table 1: Chemical, physical and microbial characteristics of bathing water, groundwater (drinking water) and harvested rainwater (HRW) for untreated and treated with sodium hypochlorite.

Parameter	Unit	Bathing water*	Groundwater	Untreated HRW	Treated HRW
pH	Range	6.5-8.5	6.5-7.10	7.1-8.7	6.9-8.38
Electrical Conductivity	mS/cm	3000	729±42	278±19	197±34
Turbidity	NTU	5	0.28±0.07	0.27±0.05	0.34±0.07
TSS	mg/L	-	12±1	17±1.4	25±3
Alkalinity	mg/L	200	234±16	97±7	63±13
Total hardness	mg/L	600	291±20	113±8	75±15
Chloride	mg/L	-	51±3	20±1	20±2
NO_3-N	mg/L	5.6	6.91±0.76	2.26±0.16	1.28±0.19
NH_4-N	mg/L	-	0.34±0.13	0.17±0.04	0.05±0.01
PO_4-P	mg/L	-	0.09±0.02	0.07±0.01	0.03±0.01
COD	mg/L	-	28.29±3.03	20.99±1.59	18.59±1.32
TOC	mg/L	-	14.4±1.08	11.31±0.28	12.94±0.41
Lead	mg/L	-	2.09±0.38	1.70±0.18	1.46±0.10
Chromium	µg/L	-	4.45±0.76	3.70±0.39	1.69±0.20
Nickel	µg/L	-	4.49±0.53	2.71±0.29	1.69±0.08
Copper	µg/L	-	5.00±0.84	3.34±0.34	4.60±0.91
Manganese	µg/L	-	19.84±3.79	11.16±2.04	1.07±0.10
Total Coliform	MPN/100 ml	500-2500	1552±357	4304±785	<1
Residual chlorine	mg/L	-	-	0.10±0.01	0.65±0.16
BOD	mg/L	≤3	-	0.33±0.03	0.16±0.05
DO	mg/L	≥5	-	6.39±0.07	6.51±0.12

* Water quality standards for bathing or recreation, India (CPCB, 2009).

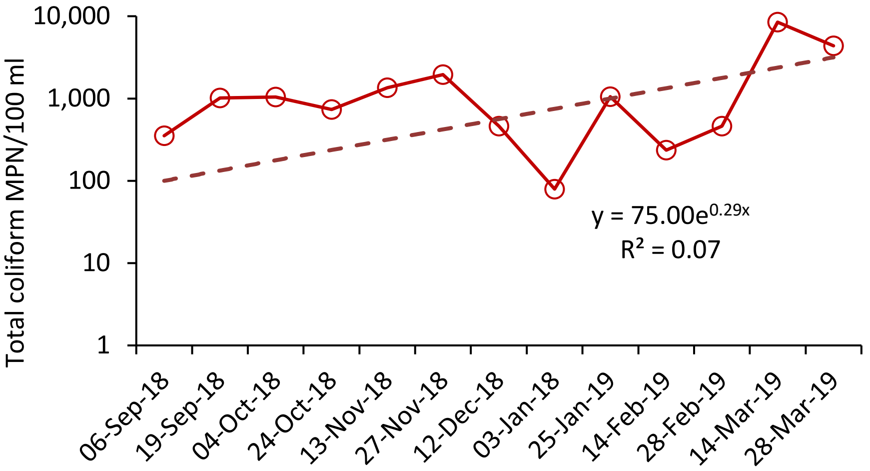

Figure 1: Total coliform population and growth in the stored rainwater. The dips in total coliform indicating dilution caused by the accidental mixing of village water with the harvested rainwater. Receiving village water that can be stored in a separate tank in rural India is a common practice for this region of the study.

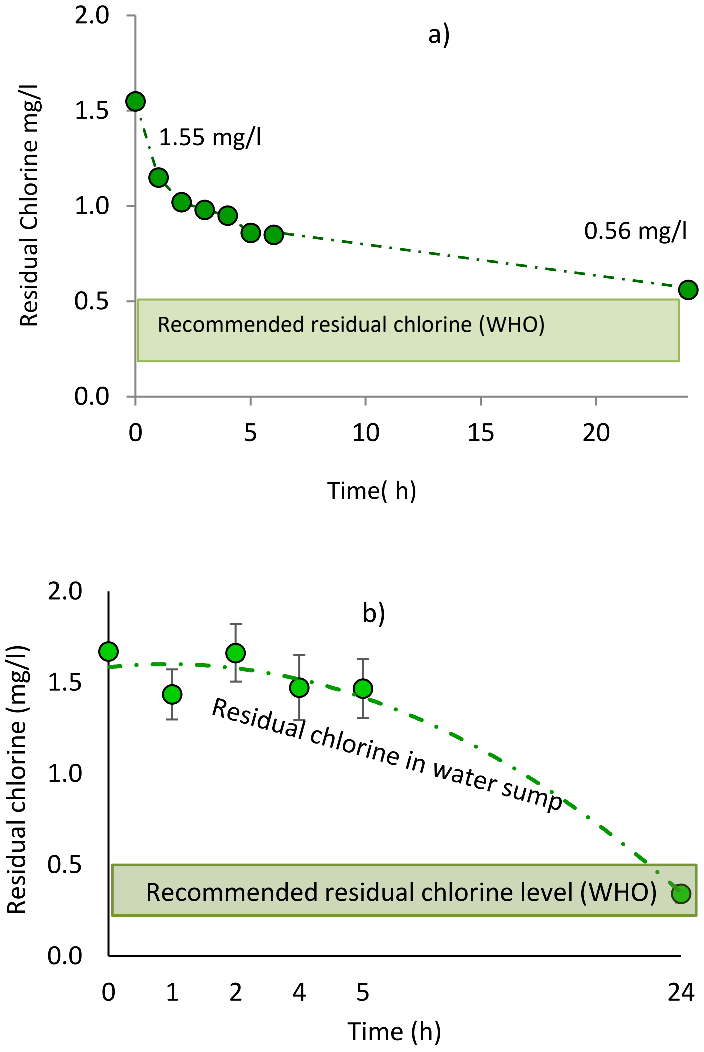

Figure 2: a) The consumption of residual chlorine in a small volume of rainwater for 24h under controlled laboratory conditions; b) Residual chlorine level ± the standard of errors during the first 24h of treating the harvested rainwater in the sump with sodium hypochlorite, indicating that residual chlorine is lower than in the controlled laboratory work, however, it is still within the required level by the WHO for drinking water.

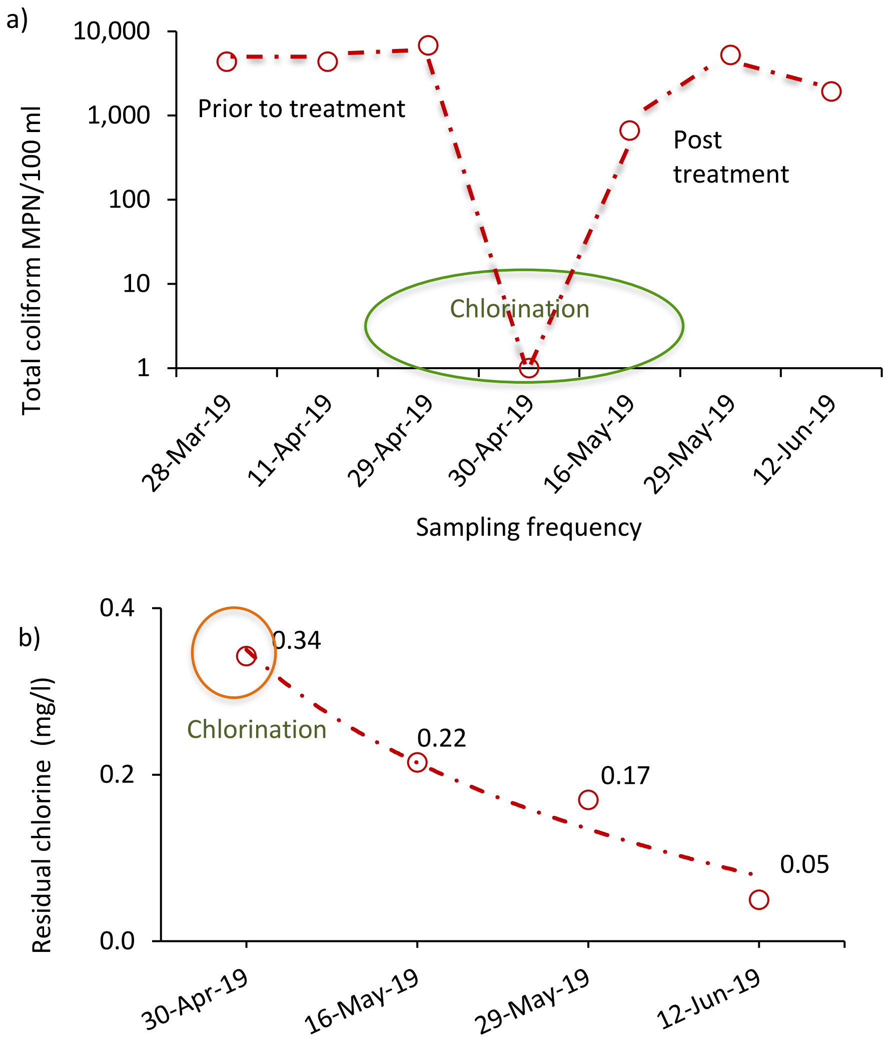

Figure 3: a) Microbial abundance prior, during and post chlorination treatment; b) residual chlorine consumed by contaminants in the rainwater stored in the sump.

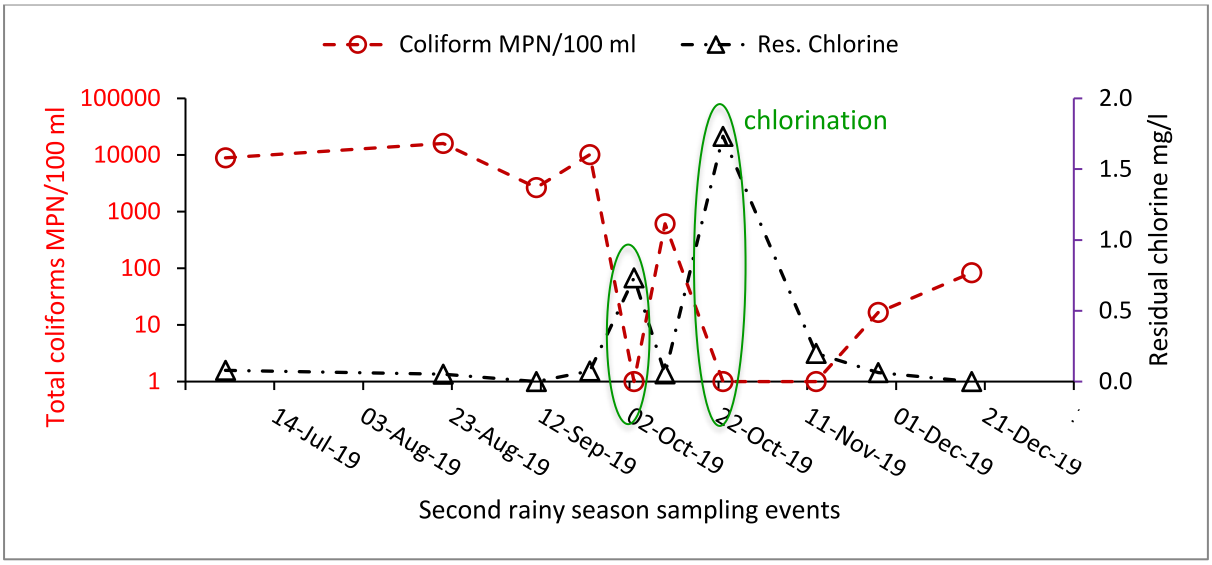

Figure 4: Illustrates second year's coliforms counts (primary axis) and residual chlorine (secondary axis) in the sump water before and after chlorination events, which inversely correlates with residual chlorine levels of the harvested rainwater 2 (HRW2).