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Original Research

Assessment of Filtration System Efficiency of Artificial Groundwater Recharge Wells in Lahore

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Abstract

Groundwater recharge is an important process that naturally maintains both water quantity and quality in a given aquifer. However, aquifers of mega cities are shrinking owing to poor urban-water planning and management especially due to lack of surface rainwater recharge systems. Therefore, this study was designed to evaluate the efficiency of filtration system of artificial groundwater recharge wells which is the most viable surface rainwater harvesting (RWH) techniques in urban areas. Henceforth, a total of two artificial surface recharge wells were selected for water sampling from five different points namely rain-gauge, runoff, silt trapper, roughing block and invert well during Monsoon Season in Lahore and characterized in terms of Physico-chemical and microbial parameters. These recharge wells were monitored to evaluate real-time pollutants filtration potential of storm water after every episode of rain. The results revealed that, overall recharged water quality after filtration was quite satisfactory because filtrate media drastically reduced the turbidity level in all examined samples. Other parameters were also within permissible limits according to drinking water quality standards. Overall, 92.5%, 62.7%, 50.06%, 21.42%, 50%, 16.6%, 90% and 99% reduction in turbidity, conductivity, TDS, Na, K, Ca, NO_3 and coliform respectively was achieved using installed filter media which was significant statistically ($p<0.05$). Henceforth, artificial groundwater recharge well is a sustainable, cost-effective tool that reduces burden on urban aquifer, alleviate energy consumption and manage urban rainwater runoff quality without polluting the aquifer.

Keywords: rainwater harvesting, groundwater recharge well, filtration system, surface runoff, water quality

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Introduction

Water scarcity and contamination is one of the major environmental issues of the modern world followed by unequal distribution of resources, overpopulation and climate change [1-3]. Based on United Nation's report Published in 2012, global urban population is estimated to reach 6.3 billion by 2050 whereas two third of the world population will face water shortage by 2025 [4]. Pakistan being an agriculture-based economy will suffer from the future water shortages as it is currently extracting $35x10^3$ hm^3/year of groundwater for agricultural use only [5-6]. The per capita water availability has reduced significantly over time in Pakistan i.e. from 5,600 m^3/person in 1947 to 1,038 m^3/person in 2010; this is expected to further decline to 575 cubic feet/person by 2050 [7]. Similarly, speaking in terms of water quality; only 20% of urban population has access to clean drinking water owing to industrial activities in the cities of Pakistan. Rural areas on the other hand, i.e. about 7% rely upon groundwater and in some cases surface water for drinking purposes [8-9]. Hence, waterborne diseases such as endemic diarrhea is causing up to 2.5 million deaths each year due to unavailability of clean drinking water [10]. Moreover, deteriorating water quality is affecting each and every walk of life thereby limiting economic growth, agricultural production while increasing infant mortality rate among many other issues [11].

Groundwater aquifers are one of the largest reservoirs and sources of freshwater i.e. it contains more than 98% of the total freshwater on earth [12]. However, the formation and replenishment of these aquifers requires hundreds of years due to complex and diverse stratification of the earth crust consisting of both saturated and unsaturated zones [13-14]. Precipitation in terms of rainfall is a usual source for groundwater recharge. In Pakistan, 50 to 75% of rainfall is associated with summer and winter monsoon seasons [15]. However, as a result of poor water planning and management, the rain water received in monsoon seasons is wasted and also causes urban floods in densely populated cities creating further problems i.e. damage to the property, waterborne diseases, electricity related accidents and increased road accidents. Similarly, it has also been predicted that about 50% of the total population will start living in urban areas by 2030, which will worsen the situation further in terms of water quantity and quality [16-17].

Learning from nature i.e. collecting rainfall runoff followed by filtration is an environmental friendly, sustainable and cost effective method that can be used for urban runoff water recycling and groundwater recharge. Hence, Artificial Rainwater harvesting system, once installed in cities, can provide numerous benefits namely runoff water filtration, groundwater recharge, resource recycling, maintenance of water table, energy saving, avoid land subsidence and decrease burden on conventional water supply schemes among others [18-20]. Owing to these advantages, old civilizations from Egypt, Palestine, Greek, Iran, Iraq, Yemen and Europe use to had schemes for runoff reuse preceded by filtration and storage. Moreover, countries such as Japan, Australia, South Korea, Thailand, China, Taiwan, United State, Nigeria, Zambia and Jordan are promoting rainwater harvesting due to water shortage [21-22]. These countries are saving great amount of water and energy at the same time by recycling and reusing rainwater. According to Australian Bureau of Statistics about 1.7 million houses have fitted rainwater tanks in their building and approximately 41% of urban horticulture is maintained in Rome through harvested rain water [23-24].

Pakistan is also facing the same challenge as according to WASA (Water and Sanitation Agency), the water table level is reducing with an average of 3.03 feet per annum. The natural sources recharging Lahore aquifer are: rainfall, River Ravi and irrigation branch canals (Upper Chenab Canal and canal water distribution system) [25]. The River Ravi which originates from India is one of the major sources of recharge of Lahore aquifer system, but the surface flows of river were reduced to almost zero by 2000 due to the construction of Thein dam by India. This resulted into substantial lowering in water table in river adjoining area of Lahore city [26]. Moreover, pollution level of Ravi is very high because agricultural and industrial waste is dumped into Hudiara Drain by both India and Pakistan making the river highly polluted [27-28]. However, Lahore receives a significant amount of rainfall (maximum daily rainfall ranges from 29 to 211mm with an average of 80mm) during monsoon period which contributes 40% to groundwater recharge annually [29] but unfortunately a huge amount of rainwater runoff gets wasted and mixed with sewage water owing to poor urban water planning and management. This specifically is due to lack of recharge wells.

However, harvested water may get contaminated during its flow and pose a threat to the aquifer. Therefore, filtration system must be present in recharge schemes to achieve required water quality targets. Henceforth, the current research was designed to investigate the efficacy and performance of filter media fitted in groundwater recharge wells in the city of Lahore, Pakistan. These groundwater recharge wells were installed in early 2000's by Pakistan Council of Research and Water Resources (PCRWR), a government run research institute for water sustainability. The water samples were collected from five different points namely rain-gauge, runoff, silt trapper, roughing block and invert well in order to evaluate varied levels of pollutants present and their removal efficiency by the filtration media. The removal efficiency was estimated by analyzing the physical, chemical and microbial parameters before and after passing through the filter media and compared with Punjab Environmental quality standards (PEQS) as well as that of World Health Organization (WHO). The paper in hand carries great significance in terms of water resource management and planning for Lahore city having inadequate drainage infrastructure, poor water quality, depleting water table and limited water availability.

Materials and Methods

Study Area

The study area consists of Lahore which is geographically situated between 31°15'-31°45'N latitude and 74°01'-74°39'E longitude. The total area of the city is 1772 km^2 having hot semiarid climate with mean annual rainfall of 675 mm, varying from 300-1200 mm and average annual temperature of approximately 24ºC [9]. The bed rock is constituted of the unconsolidated alluvial complex of contemporaneous filling of subsiding trough- mainly composed of sodium and calcium bicarbonates. The sediments have been deposited by the present and ancestral tributaries of the Indus River during Pleistocene-Recent periods. The alluvial complex is heterogeneous and individual strata have little lateral or vertical continuity but on regional basis it behaves as a homogeneous aquifer and the presence of silt and clay do not impede the flow of groundwater, considering long-term pumping [30].

Lahore is the second biggest city in Pakistan and provincial capital of the Punjab province. The city's population is about 11.12 million people accommodating 82% of the urban population of Punjab alone. The land cover of the city has changed as more than 1200 hectares of agricultural and forest land is acquired for urban use each year and impervious surface has increased by 11.9% reducing the natural recharge (Ahmed et al, 2001). Groundwater is the only source of fresh water supply and approximately 3500 Acre Feet (AF) of water is extracted per day from 1800 public and private tube wells resulting into the water table level decline [9, 29].

The following groundwater recharge wells with pre filtration system were located in Lahore namely:

Site 1: PCRWR Regional office, Raiwind Road

Site 2: STEDEC office Gaddafi Stadium Ferozpur Road

Project Description

Site 1 is located near Raiwind road having four blocks of filtration system namely Silt Trapper, Roughing Filter, Fine Filter and Media Filter which are installed 15 feet deep down into the ground. Each block is made up of different filtering materials which are natural and readily available. Runoff enters from surface, lawns in first block (silt trapper) through 6-inch bore opening where sediments are settling down and remaining water moves to the next block. Roughing filter have 3 layers of natural filtration materials including crushed stone having particle size 3/8"; crushed stone having particle size 1/2"and the 3rd layer is made up of boulders. Fine Filter has almost same filtering material with one extra layer of 8" of chips #9 in addition to 6 inches thick layer of crushed stone 3/8" in particle size, 1.5'(feet) thick layer of crushed stone 1/2" in particle size and finally a 6 inches thick layer of boulders. Media Filter is made up of 2'(feet) thick layer of silica sand and remaining part of block covered with crushed stones. Runoff water after passing through these specialized filtration blocks enter into recharge

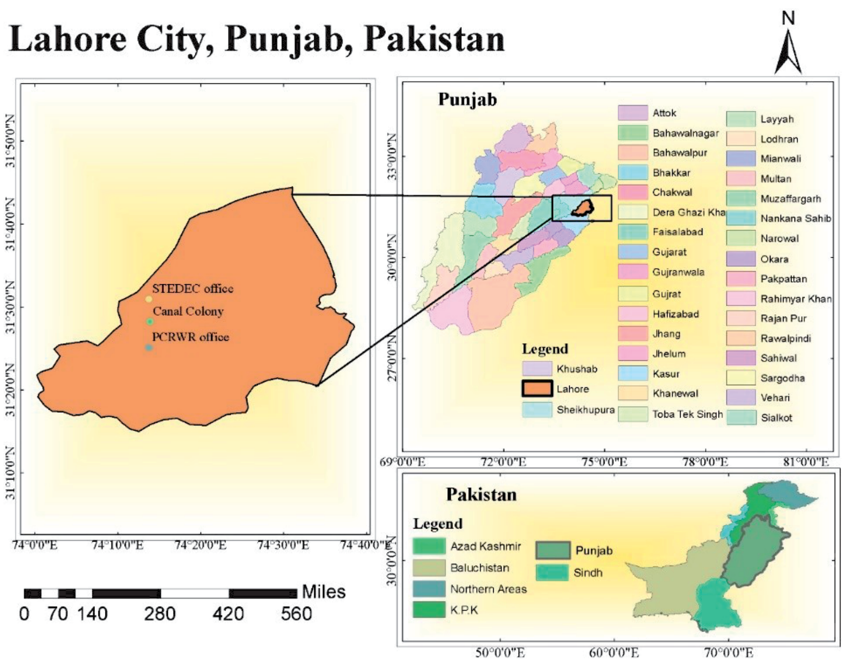

Fig. 1. Map of study sites.

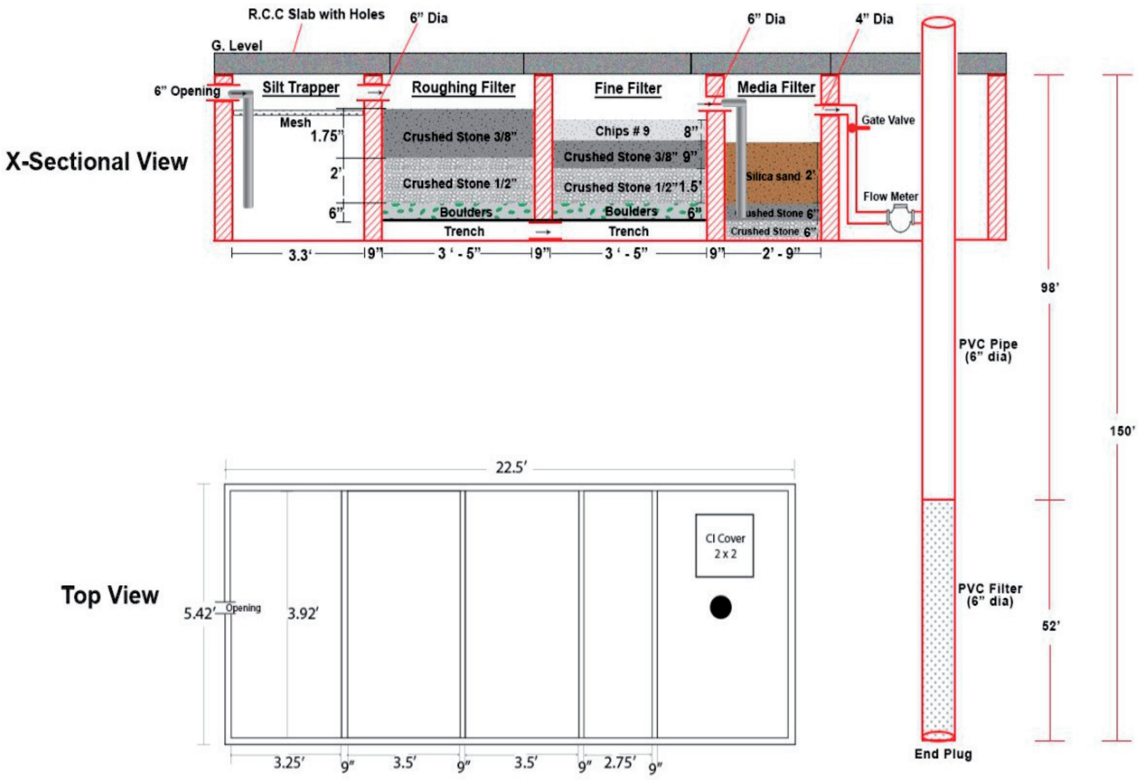

Fig. 2. Schematic diagram of filtration system with recharge well in site 1.

well which constitutes of a PVC (polyvinylchloride) pipe 6" (inches) in diameter and lowered up to a depth of approximately 150'(feet). The recharge well bore is drilled through cable method during which chemical analysis of samples is done through sampling at various depths, i.e. every 10 feet up to a final depth of 150 feet (Al-Othman 2011). Water flow meter (volume basis) is also installed. The schematic diagram of filtration system with recharge well for site 1 is shown in Fig. 2.

Site 2 is located at Ferozepur Road near Qaddafi Stadium having 3 blocks of filtration system i.e. Silt Trapper, Roughing Filter and Fine Filter which are 6.5'−feet deep from the ground with the first 2 blocks of filtration material. The recharge well has Fine Filter having 9" inches thick layer of silica sand filtering material coupled with 1 feet thick layer each of chips #9, crushed stone 3/8" and crushed stone 1/2" as well as a 6" inches thick layer of boulders. Runoff water after passing filtration blocks move towards invert well that is made up of PVC (polyvinylchloride) pipe having 6 inches and drilled down to a depth of about 160' feet. The schematic diagram of filtration system with invert well of site 2 are shown in Fig. 4.

Samples Collection

Water samples were collected from both sites at five different points namely rain gauge sample (representing rainwater), surface catchment area sample representing surface runoff water before entering into the filtration system, slit trapper block sample, followed by roughing filter block and fine filters block samples (sampled from surface water runoff passing through the different filtration blocks). These samples were collected in polyethylene bottles of 1000 ml, 500 ml and 250 ml during summer monsoon in triplicates. Water samples were also taken from recharge well (surface runoff rain water after crossing the filtration system) through

Fig. 3. Stepwise execution of Groundwater recharge well at PCRWR, Lahore.

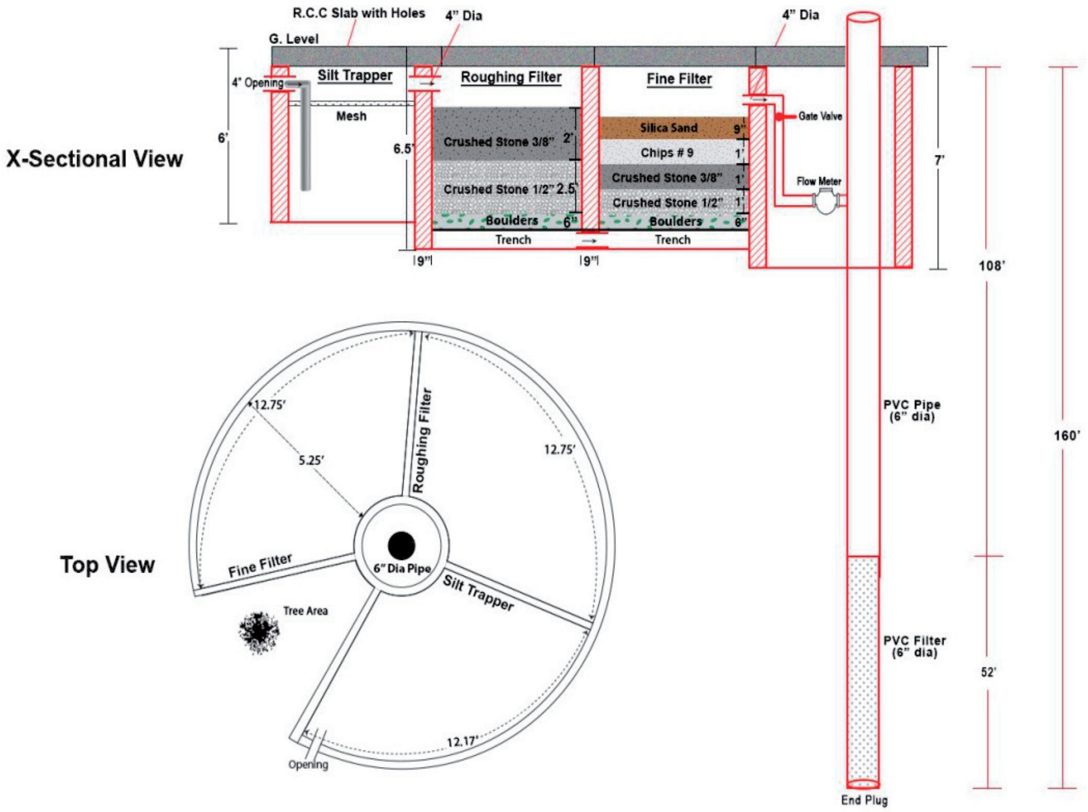

Fig. 4. Schematic diagram of filtration system with recharge well in site 2.

sampler in Plastic bottles in triplicates during summer monsoon (July, August, September).

Testing and Analysis

Water samples were immediately brought into the laboratory at Pakistan Council of Research and Water Resources (PCRWR) and at University of Veterinary and Animal Sciences Lahore (UVAS) for Physico-chemical analysis using standard methods recommended by APHA 20th Edition 1998 (Table 1) [31].

Table 1. Measuring parameters and their test methods.

Parameters	Testing Method
pH	4500 H-B, Electrometric Method
Electrical Conductivity	2510-B, Laboratory Method
Total Dissolved Solids (TDS)	2540-C TDS at 180 degree Celsius
Turbidity	2130-B, Nephlometric Method
Alkalinity	2320-B, Titration Method
Nitrate as N	4500 NO3 –B Ultraviolet Spectrophotometric Screening Method
Chloride	4500 Cl-B, Argentometric Method
Carbonate and Bicarbonate	2320- B, Titration Method
Hardness	3500-Ca-D, EDTA Titrimetric Method
Sulfate	4500 SO4-E, Turbidimetric Method
Na, K and Ca	3500 Na-B, 3500 K-B Flame Emission Photometric Method, 3500 Ca-D EDTA Titrimetric Method
Total Coliform and Fecal Coliform	9222 B & D, Standard total and Fecal Coliform Membrane Filter Procedure

Statistical Analysis

Descriptive statistics was used to get mean, standard deviation and standard error in the readings of the triplicates of measurements made. The analysis of variance (ANOVA) routine of the Design Expert 8.0 software was used to work out the significance of filtration system for the removal of physico-chemical and microbial pollutants [32].

Results and Discussion

Surface runoff rainwater harvesting through recharge wells is an ecofriendly and sustainable solution for urban water management. However, the efficiency of filter media fixed in recharge well is crucial in maintaining the groundwater quality, therefore, it was analyzed in terms of physical, chemical and microbial parameters before and after passing through the filter media. Figs 6 to 11 show box-whisker plots of pH, conductivity, turbidity, hardness, alkalinity, TDS, Na^+, K^+, Ca^{2+} $Mg^{2+}$and total bacterial count. The box contains lower and upper quartiles and the interior line is the median value. The lower and upper lines out of each box present the minimum and the maximum, respectively.

The most generally used parameters to determine the rainwater quality for its suitability for various purposes are pH and turbidity. Fig. 5a) showed that all tested water samples (site 1) had pH value ranging between 6.6-8.0 which were within the recommended limit (6.5-8.5) except in the month of July, where the rain water samples were slightly acidic due to first flush effect and a gap in precipitation event. The pH of harvested water becomes neutral to basic after passing through the filter media, which may owe to the dissolution of anions from filtration material due to its basic composition (clay, gravel, silica sand). The water samples at Site 2 (Fig. 5b) showed variation in pH (acidic) over time as well as within different filtration blocks due to the poor maintenance practices which is also statistically significant (<0.05).

The turbidity values of all tested water samples ranged from 3 NTU to 89 NTU. The turbidity of

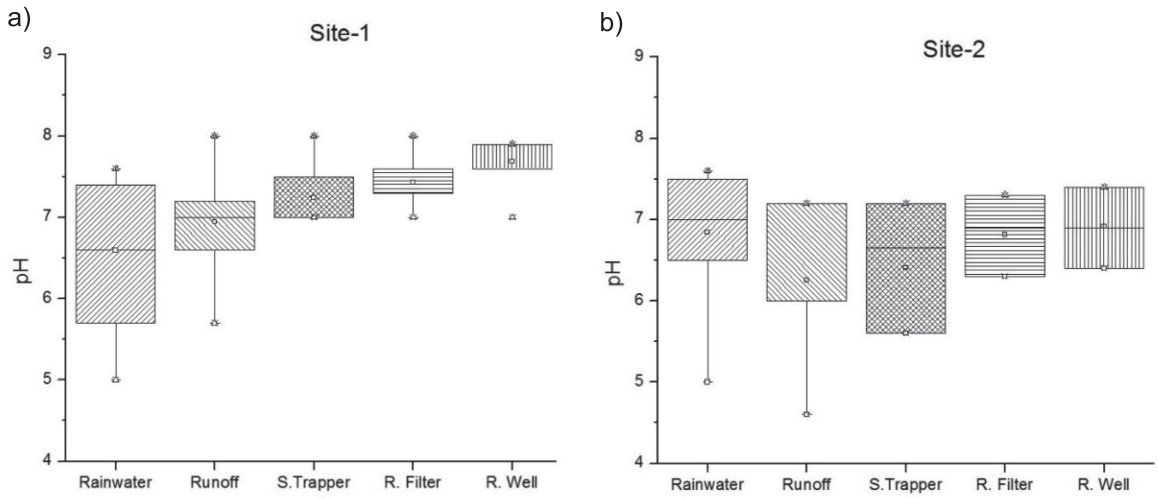

Fig. 5. Monthly average pH values of rainwater and at various filtration blocks of artificial recharge wells at PCRWR and STEDEC.

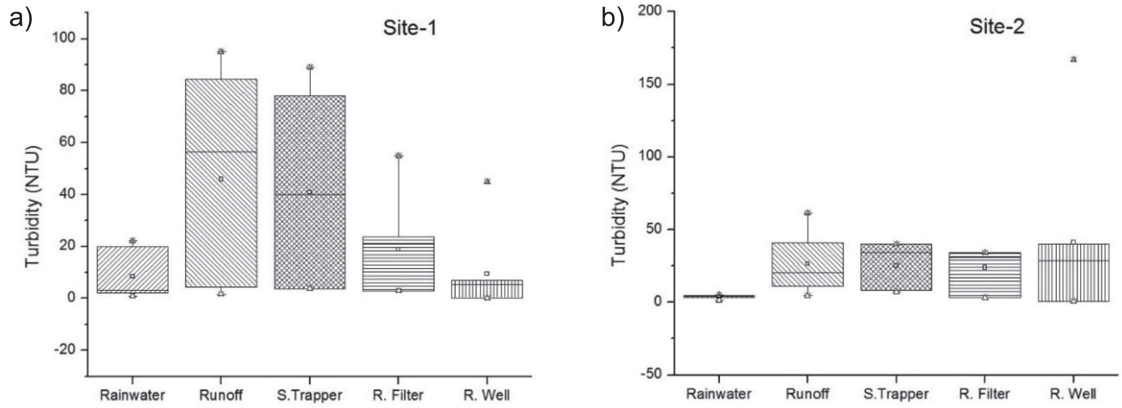

Fig. 6. Monthly average turbidity values of rain water at various filtration blocks of artificial recharge wells at PCRWR and STEDEC.

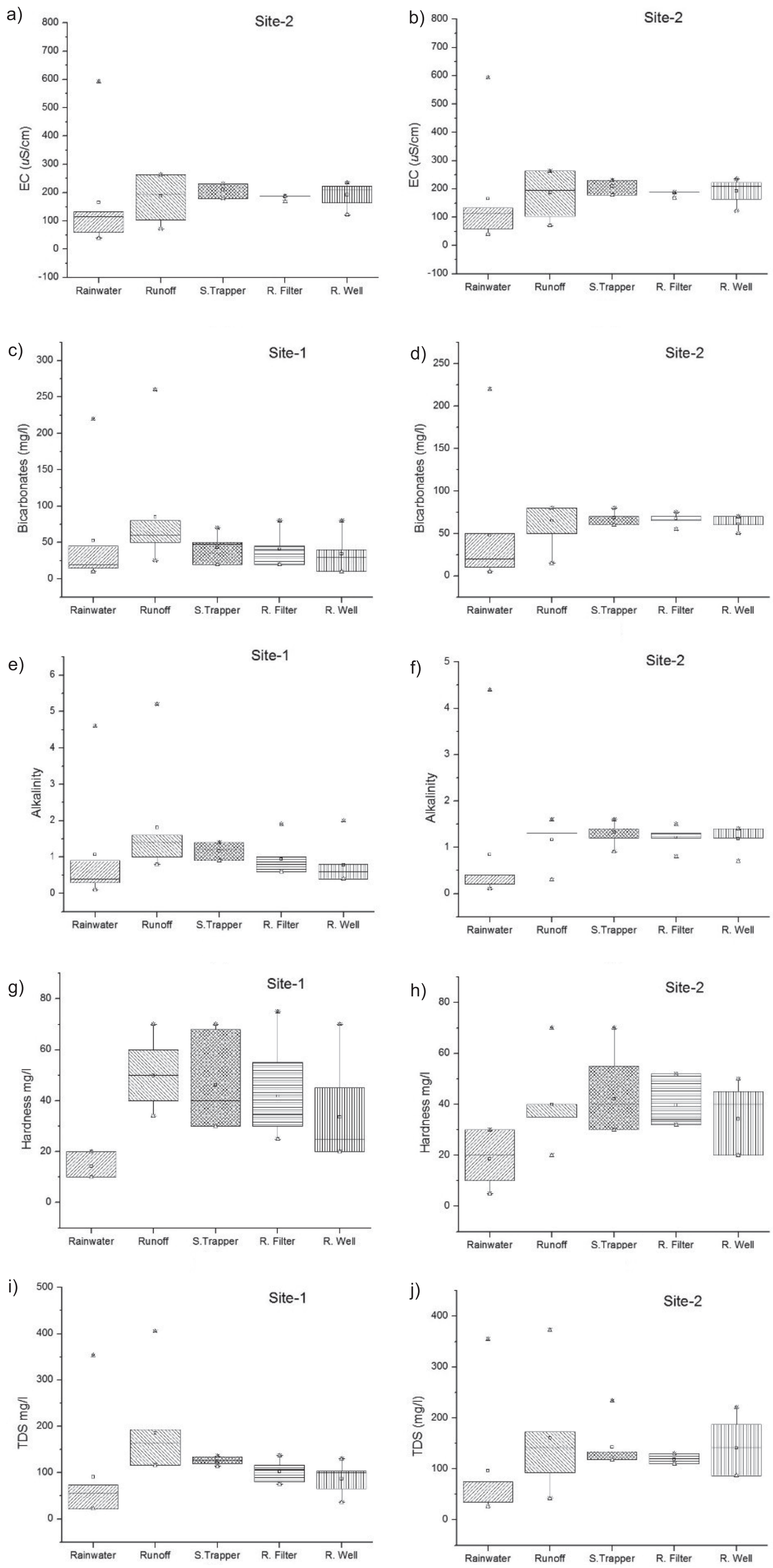

Fig. 7. Monthly average values of EC, TDS, Alkalinity, Hardness and bicarbonates of rain water -at various filtration blocks of artificial recharge wells at PCRWR and STEDEC.

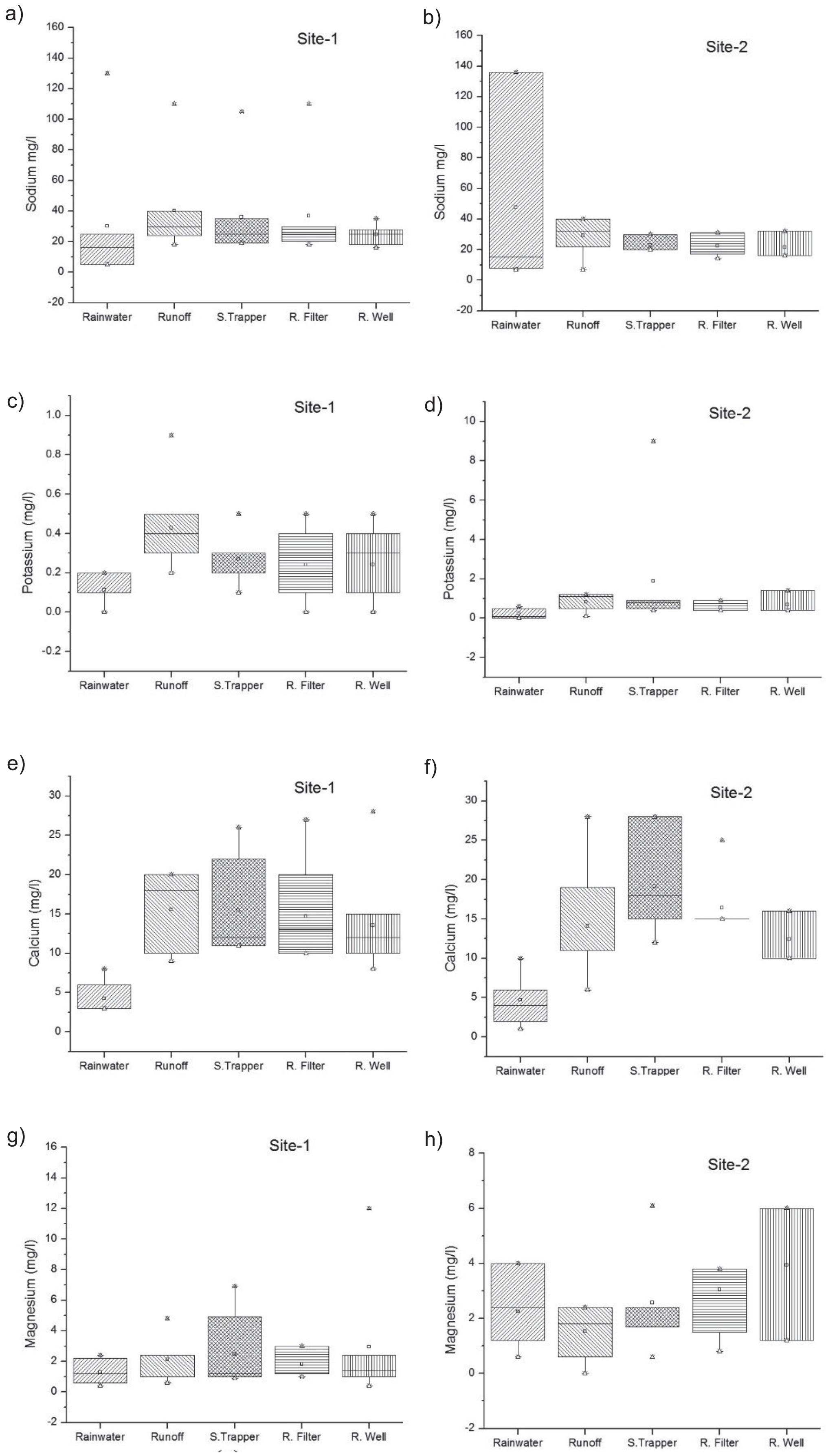

Fig. 8. Monthly average values of Na, K, Ca, Mg of rain water at various filtration blocks of artificial recharge wells at PCRWR and STEDEC.

rainwater is significantly lower than runoff water ($P<0.05$) which may be due to the dissolution of impurities, sediments and particulates from catchment area as well as other environmental factors as shown in Fig 6. However, turbidity values were reduced significantly after passing through the filtration media and reached within the permissible limit (<5NTU) because of the removal of silt and floating materials by silt trapper, roughing filter and fine media filters, as sand filter is very effective for turbidity removal [33]. At Site-1, 100% removal efficiency was observed due to cleanliness, maintenance and design of filtration block. However, at site 2 the turbidity values were much higher due to the mixing of dirty water from adjacent sides and uncovered filtration blocks (no lids). Therefore, maintenance and cleanliness of filtration blocks is necessary after every monsoon period for increased sustainability of recharge wells. Furthermore, turbidity issue maybe overcome through sedimentation, as pollutants settle down earlier rather than fastly moving forward through filtration blocks whereas alum or calcium hydroxide promotes settling of small suspended particles [24].

The Electric Conductivity (EC) range of water samples collected from different points was 40-298 µS/cm indicating that the ion concentration was low, however,

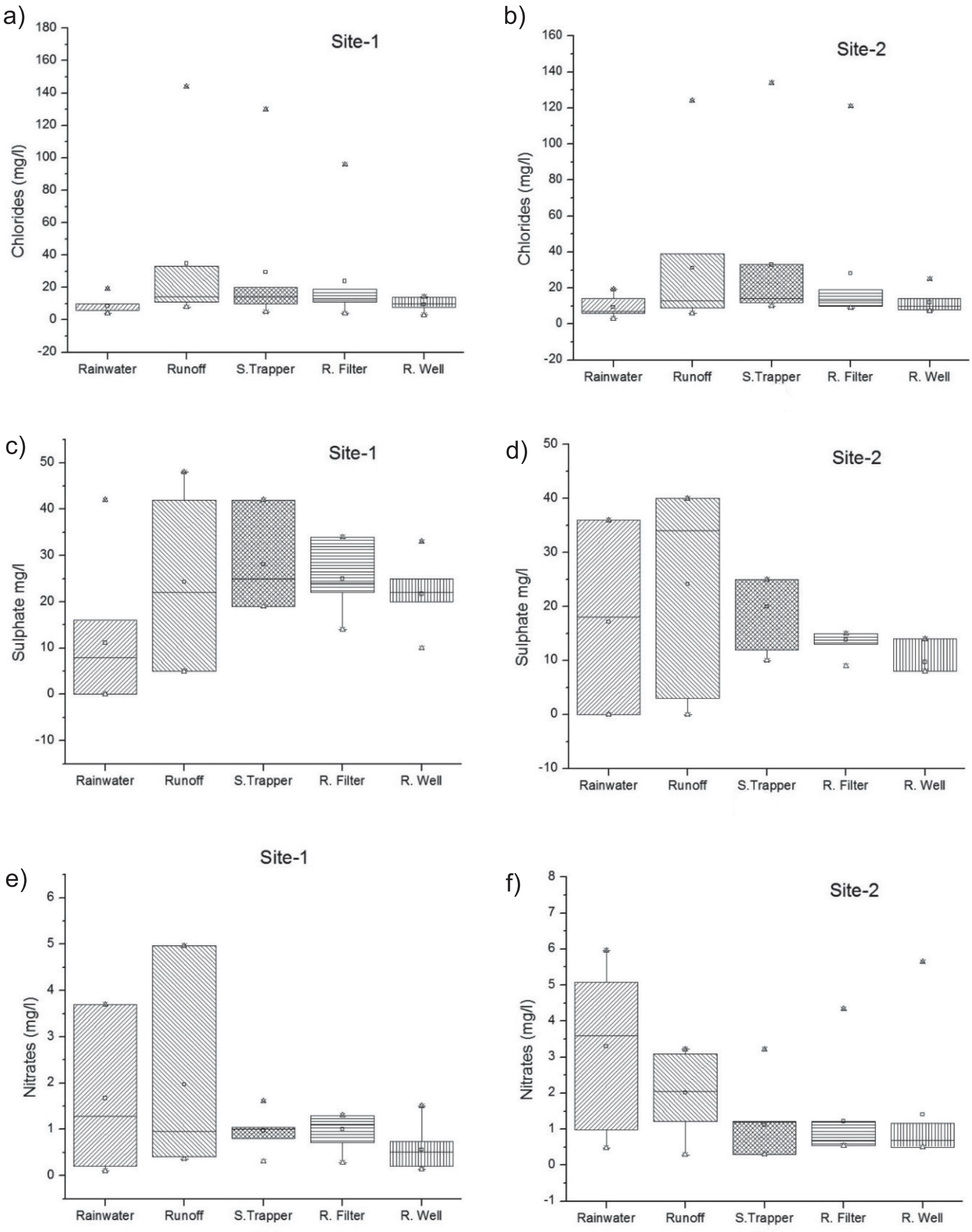

Fig. 8. Monthly average values of Na, K, Ca, Mg of rain water at various filtration blocks of artificial recharge wells at PCRWR and STEDEC.

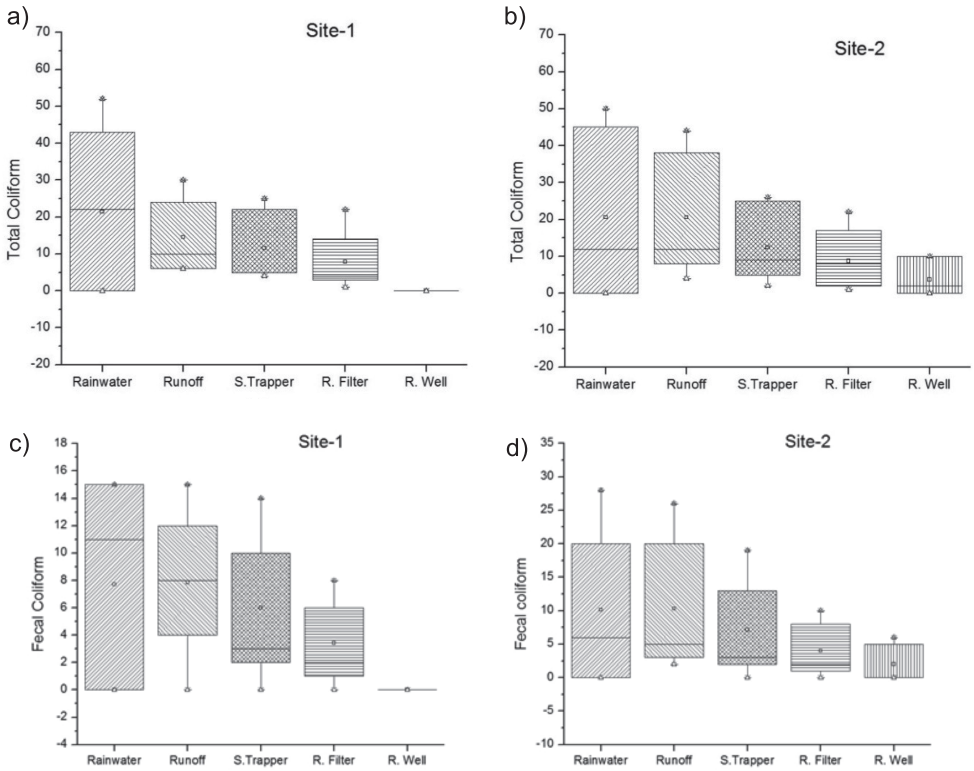

Fig. 10. Monthly average values of total coliform and fecal coliform of rain water at various filtration blocks of artificial recharge wells at PCRWR and STEDEC.

increase in EC from rainwater to runoff (EC = 95 to 259 µS/cm at site 1; EC = 104 to 227 µS/cm etc). suggested the dissolution of some substances from the catchment area which is statistically significant ($P<0.05$). These values, even then, were within permissible limits and filtration media further lowered them as indicated in Fig. 7 (a, b). Similar trends were observed for Total Dissolved Solids (TDS), Alkalinity, Bicarbonates and Hardness (Fig. 8 (c-j)).

The variations in the concentrations of major cations (Na, K, Ca, and Mg) in rainwater and harvested water are given in Fig. 8 (a, g). In rainwater and harvested water, sodium concentration ranged between 5 mg/l to 70 mg/l; Calcium concentration varied between 1 to 50 mg/l; Potassium concentration ranged between 0 to1.5 mg/l and Magnesium from 0.4 to 8.4 mg/l. The concentrations of these cations were significantly lower in rainwater as compared to runoff water ($p<0.05$) but filtration media further lowered these values. However, all samples collected from five different points met the drinking water quality standard of PEQS and WHO in terms of these major cations.

Fig. 9 (a-f) shows the concentrations of major anions (chloride, sulfate and Nitrate as N) in water samples collected from five different points. Sulfates range between 0 to 48 mg/L, Chlorides between 3 to 144 mg/L and Nitrates between 0.101 to 7.96 mg/L in all collected water samples which were far below the permissible limits. However, the concentrations of these anions slightly increased from rainwater to runoff due to the addition of impurities from catchment areas but decreased after passing through the filtration media. All the water samples collected were within the drinking water permissible limits for chlorides, sulphates and nitrates.

The microbiological parameters including total coliforms and fecal coliform were measured to assess the extent of microbiological contamination of the water which must be zero in drinking water according to WHO. Results revealed that coliforms were detected in majority of rainwater samples which might be due to the interaction of vectors such as flies, birds and mosquitoes with uncovered rain gauge bottles as the sampling area was located near lawn and poor cleaning practices were also observed especially at site 2. Moreover, less rainfall (<0.05 mm) and high temperature also promote the microbiological growth (Norman et al. 2019). However, there was a drastic decrease in coliform level (rain gauge = 52, runoff = 24, silt trapper = 22, roughing filter = 14 and media filter = 0,) and fecal coliform (rain gauge = 15, runoff = 12, silt trapper = 10, roughing filter = 6 and media filter 0) after passing through the filtration system (fig. 10 a and 10 b) and reduced to zero after crossing the media filter because the existing bacteria co-migrate with the settleable particles as sedimentation is the primary mechanism of microbial removal [34] . At site 2, 71% of collected water samples had zero total coliform and 29% were beyond the safe limit which is statistically significant ($p<0.05$). Similar trend was observed for fecal coliform.

Conclusion

Rainwater harvesting is one of the most promising alternatives to supply fresh water to cope up with water scarcity and receding water table issues. This study was aimed to assess the efficacy of filtration system present in recharge wells for surface rainwater harvesting of two sites (PCRWR and STEDEC) at Lahore, Pakistan. The results show that the chemical quality of harvested water is quite satisfactory after passing through the filtration system as all the analyzed parameters came within permissible limits of PEQS and WHO. The filter media performance was also favorable as the turbidity values were drastically decreased to acceptable value (<5NTU) after passing through it. The percentage removal of contamination was about 55%-90% which brings recharging water within water quality standards except for coliform count which were detected in most samples. However, coliforms were effectively removed by the filter media as the present bacteria co-migrate with the settleable particles through sedimentation. Therefore, the rainwater harvesting schemes must be accompanied by filtration system along with biofilter before draining it into the recharge well or storing it for other purposes. Moreover, these systems must ensure regular cleaning of catchment area to avoid or reduce the addition of contaminants in harvested water. Consequently, surface runoff rainwater harvesting through recharge wells in the city shall emerge as ecofriendly and sustainable technology capable of catering city's demand for water as it is locally available, cost effective and safe method to recharge the aquifer.

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Conflict of Interest

The authors declare no conflict of interest.

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