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Feasibility of managed domestic rainwater harvesting in South Asian rural areas using remote sensing

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ABSTRACT

Rainwater harvesting is a simple, low-energy and cost effective solution for meeting drinking and domestic water demand in rural communities. In this study, the feasibility of Domestic Rainwater Harvesting (DRH) in South Asia region was assessed using rainfall climatology, remote sensing and water balance concept to improve the rural public health condition. Long term satellite precipitation data was used for analyzing the precipitation climatology as in situ stations are sparsely located in this region. The study area was divided into smaller regions and average roof area for each region was approximated from the satellite visible imagery. It was found that DRH is a viable option in most of Bangladesh, Sri Lanka, Himalayan range, North-Eastern, Central, Eastern and coastal parts of Southern India as the rainfall and household architecture can satisfy potable (7.5 liters per capita per day-lpcd for drinking and cooking) water demand for significant portion the year even in worst case scenario. The study demonstrated that DRH system is not a realistic option in most parts of Pakistan, Northern and Western India. DRH would not a feasible option to fulfill the domestic (20 lpcd for drinking, cooking and basic hygienic needs) water demand for significant portion of the year except North-Eastern India. This study is perhaps the first comprehensive assessment of rainwater harvesting potential in rural South Asia using satellite-precipitation climatology and can inform the policy makers on where to invest geographically for building distributed rainwater harvesting systems.

1. Introduction

Water supply, sanitation and hygiene (WASH) are foundational issues related to public health. Development of water supply is a prerequisite for robust sanitation system and hygiene practice (Hunter et al., 2010). The world has met the Millennium Development Goal target for safe drinking water coverage in 2010 (UNICEF and WHO, 2015). However, 748 million people still lack access to improved drinking-water (WHO/UNICEF, 2014) and 1.8 billion people drink water from a source with fecal contamination (Bain et al., 2014). Children under five years old in the low and middle-income countries are the major victims and account for more than 90% death from water-related diseases such as diarrhea caused mainly by drinking fecally contaminated water (UNICEF, 2003). Safe water at households prevents waterborne disease like diarrhea, typhoid and cholera (Bartram and Cairncross, 2010). Cutler and Miller (2005) claimed that clean water was the key reason behind the decline of half of the observed mortality in U.S. cities.

Water demand will increase substantially with increasing population to maintain the economic growth and meet the food demand (Vorosmarty et al., 2000). Estimates show that 60% people may face water scarcity by 2025 (Qadir et al., 2007). Developing countries of South Asia are particularly vulnerable to lack of safe drinking water due to development activity lacking coordination with water management policies. Almost 134 million people in this region do not have access to safe drinking water (UNICEF and World Health Organization, 2015). Other apparently safer sources of water, such as groundwater, have problems too. A recent study demonstrated that 60% of the shallow groundwater of the Indo-Gangetic Basin are not suitable for drinking due to salinity and arsenic contamination (MacDonald et al., 2016). The International Bank for Reconstruction and Development/The World Bank (2003) showed that more than one third of water infrastructures in South Asia are not functional. Due to these reasons people are forced to fetch water from surface water bodies which are highly contaminated with fecal organism (Luby, 2008).

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Most of the developed and industrialized countries have the centralized pipe network based safe water supply system. This kind of large scale infrastructure with water treatment facility to purify the surface water will not be suitable for the rural communities of developing countries due to socio-economic constraints (Mara, 2003). Developing this kind of water supply system for the rural regions would require huge investment which is a major constraint for developing countries. It is also unrealistic to expect the proper maintenance of this kind of system in rural communities towards sustainability of the system. Large water supply system using surface water body might also require impoundment of water which often causes social, environmental and ecological disruption.

Compared to the centralized water supply infrastructure, Domestic Rainwater Harvesting (DRH) is more cost effective, simple to manage and socially acceptable in most of the regions (Thomas, 1998). These unique features make it very suitable for rural areas of the developing countries. According to World Health Organization (WHO) rainwater is free from major impurities. However, there is possibility of mineral contamination from roof materials and microbial contamination from the feces of birds (Magyar et al., 2014; Owusu-Boateng and Gadogbe, 2015). Simple point-of-use water treatment facilities like filters or chlorination can solve this complication in-situ though. Point-of-use water treatment was found to be the most effective intervention to reduce waterborne disease like diarrhea (Fewtrell et al., 2005; Quick et al., 1999). A study on the urban water supply system of Chennai showed that rainwater harvesting combined with efficiency improvement is the best policy to meet the skill, fairness, reliability and economic criteria. (Srinivasan et al., 2010).

In most rural areas, there are two types of water supply systems: community based and household water supply system. The community based water supply system is typically built in a suitable location of a community and shared by the all people of the community. Household level water supply system can be piped network based or a tube well that supplies water within the house. In case of communal point source, safe water can get contaminated during collection and storage due to bad handling (Han et al., 1989). Studies have shown significant fecal contamination of water between source and point-of-use storage (Pickering et al., 2010; Wright et al., 2004). Supplying water to the individual household will lessen the chance of drinking water contamination during collection and storage. People's willingness to pay for water infrastructure is also likely to wane after a short period which in turn compounds the sustainable maintenance of such systems (Zwane and Kremer, 2007). On the other hand, individual household rainwater harvesting develops a sense of ownership in the consumer (Cain, 2014). Sense of ownership has a positive correlation with the user's confidence and system management (Marks et al., 2013).

DRH can also improve the overall standard of living of the rural people. Improved water supply to individual household can substantially decrease the coping cost (collection time, financial water cost, capital cost, diarrhea treatment cost) which has huge impact on the diarrhea prevalence, child nutrition condition and mortality rate (Pickering and Davis, 2012). The median coping cost of poor water supply can be equal to 12.5% of reported cash income which is higher than the utility cost in water supply in USA (Cook et al., 2016). Improvement of water supply and sanitation also has greater economic benefit. An estimation showed that every dollar invest in water supply and sanitation gives $4.3 in return (World Health Organization, 2012). Different studies have demonstrated notable water saving potential and economic gain from domestic rainwater harvesting (Imteaz et al., 2011; Rahman et al., 2012).

People have been utilizing the rainwater harvesting technique to store and supply water since ancient civilizations. Evidence of rainwater harvesting construction has found in southern Jordan which is believed to be 9000 years old (Boers and Ben-Asher, 1982). Despite huge benefits, rainwater harvesting still lacks proper recognition in water policy or investment plan (United Nations Environment Programme and Stockholm Environment Institute, 2009). The potential of domestic rainwater harvesting for supplying potable and non-potable water has been shown in many studies (Basinger et al., 2010; Chiu et al., 2015). Imteaz et al., 2013 analyzed the performance of different combinations of storage tank and catchment area for different climatic condition in Melbourne. Akter and Ahmed (2015) have assessed the rainwater harvesting potential for an urban community in Bangladesh using multi-criteria decision analysis techniques. One study indicated that rainwater harvesting system in Goa University recharged 260 m^3 of water using a 400 m^2 catchment area in 2008 (Centre for Science and Environment, 2014). Despite high population density in the capital of Bangladesh, Karim et al., 2015 showed the potential of DRH system to fulfill partial domestic demand (up to 15–20% of the time of a wet year) using 140–200 m^2 catchment area.

Most of these studies have analyzed rainfall data from gauge networks limited in sampling to test the feasibility of rainwater harvesting. Traditional gauged measurement provides the magnitude of rainfall only at a point location. In developing countries, the in-situ stations are sparsely located and often have short, incomplete records (Cowden et al., 2008). Due to poor institutional capacity and lack of collaboration between meteorological agencies, it is challenging to get long term freely available in-situ meteorological data of south-Asia with good areal coverage (Hossain and Katiyar, 2006; Hossain et al., 2007; Balthrop and Hossain, 2009). For large scale regional feasibility analysis of DRH, spatial distribution of climatology of rainfall data for whole region is required. High resolution satellite rainfall data have the potential to provide us with the spatial and temporal coverage needed for such analyses. Rainfall estimation using remote sensing is therefore more appropriate for hydrological applications in developing countries (Hossain, 2015). High resolution satellite images can be used to approximate the roof area which is a key design component of domestic rainwater harvesting.

In this study, the feasibility of domestic rainwater harvesting in South Asia was assessed by using the following: i) long-term monthly rainfall climatology from high resolution satellite data; ii) approximate roof area derived from remote sensing images, and iii) concepts of water balance used in conventional water management. Imteaz et al., 2012 indicated that monthly water balance model overestimates the size of storage tank while daily water balance model evaluates it more precisely. However, as this study focuses more on the spatial variability of a large area in a very fine resolution, the use of monthly water balance model is reasonable.

The specific science question that is addressed in this paper is – *What is the geographic variability of feasibility of domestic rain water harvesting for meeting the potable and non-potable water demand in South Asia?*

2. Study area and data

Six developing countries (Bangladesh, India, Pakistan, Nepal, Bhutan and Sri Lanka) from South Asia were selected as the study region for this paper (Fig. 1). South Asia is a densely populated region with more than 500 million people earning than a US$ 1.25 daily income (World Bank, 2013). The precipitation pattern of this region is mainly dominated by the Indian monsoon resulting huge amount of rainfall during the summer monsoon.

The Climate Hazards Group InfraRed Precipitation with Stations (CHIRPS) version 2.0 dataset was used for analyzing gridded precipitation climatology (Funk et al., 2015). The dataset covers the area from 50°S to 50°N along all longitudes. CHIRPS dataset was prepared by incorporating 0.05° resolution InfraRed (IR) satellite imagery with in-situ station data from 1981 to present. Infrared Cold Cloud Duration (CCD)

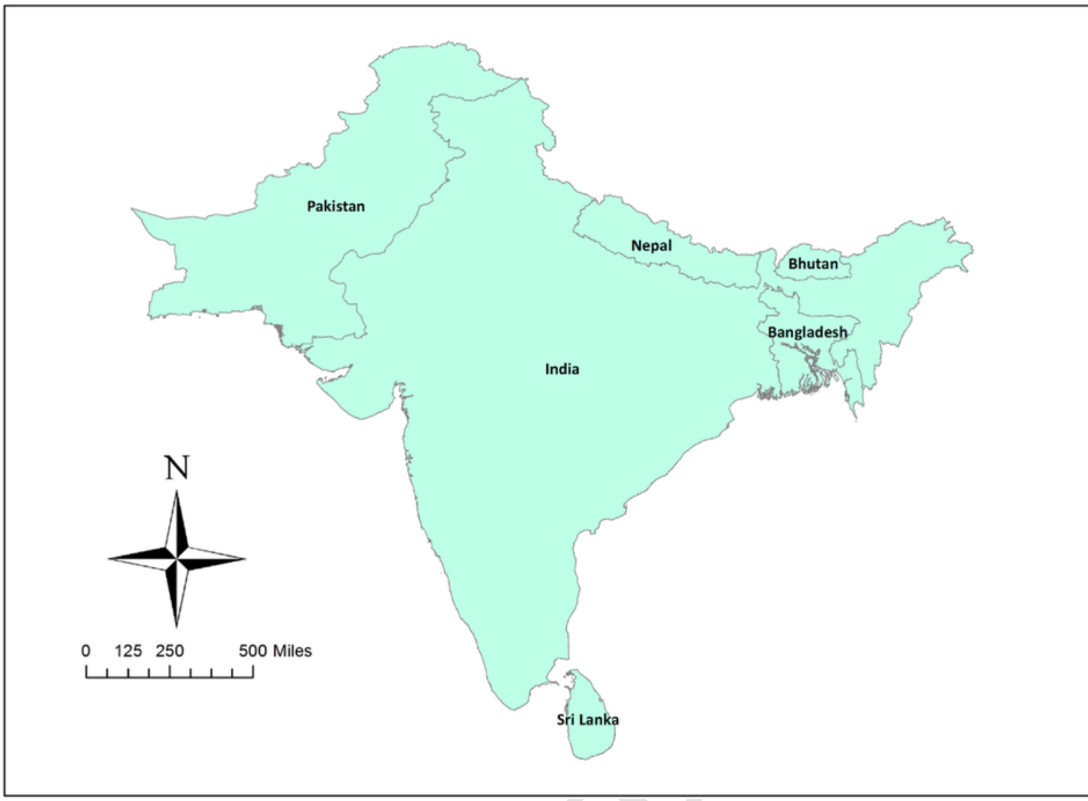

Fig. 1. Study region for exploring the feasibility of domestic rain water harvesting.

observations were used to calculate the satellite precipitation and these estimates were calibrated against the Tropical Rainfall Measuring Mission Multi-satellite Precipitation Analysis version 7 (TMPA 3B42 v7). The resolution of CHIRPS (0.05°) data is much finer than the more popular precipitation datasets like Global Precipitation Climatology Project (GPCP) (2.5°), Global Precipitation Climatology Centre (GPCC) (0.5°) and TRMM Multi-satellite Precipitation Analysis (TMPA) (0.25°). Funk et al., 2015 demonstrated that bias ratio (using GPCC precipitation as baseline) of CHIRPS was less than TMPA 3B42 v7 real-time (RT), the Climate Forecast system (CFS) and the European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis products. This fine resolution and bias corrected data gave us a unique opportunity to study the long term precipitation climatology of data sparse locations like South Asia. In this study, 0.05° resolution monthly precipitation data from January 1981 to April 2016 (i.e., 35 years) were used.

Roof samples were taken from the Google earth (http://www.google.com/earth/). Google earth is a composite platform of satellite and aerial (visible) imagery services. AeroWest, DigitalGlobe, GeoContent, Cnes/Spot Image, NASA and Terra Metrics are the main provider of images of Google Earth. The primary source of Google Earth images is DigitalGlobe. DigitalGLobe provides as high as 30 cm resolution images from their most sophisticated commercial satellite constellation in orbit. DigitalGlobe has three satellites (QuickBird, Worldview 1 and Worldview 2). Quickbird resolution is roughly 65 cm pan-sharpened (65 cm panchromatic at nadir, 2.62 m multispectral at nadir). Spot Image is a worldwide distributor of products and services using imagery from Earth observation satellites. It has 3 SPOT satellites in orbit (Spot 5, 6, and 7) provide images with a large choice of resolutions – from 2.5 m to 10 m.

3. Methodology

The general methodology of this study is summarized in Fig. 2. In this study, percent of the time of the year water demand satisfied was

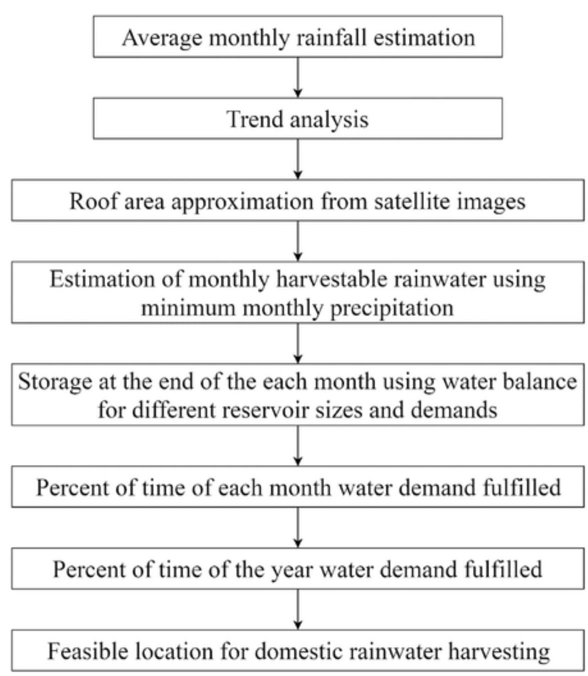

Fig. 2. Sequence of analytical steps used in the study to explore feasibility of domestic rainwater harvesting.

determine using the rainfall climatology. The details of the methodology are described in this section.

3.1. Rainfall climatology analysis

The climate of South Asia is highly dominated by the monsoons. Major amounts of the rainfall occur in this region during July to September during summer monsoon (Gadgil 2003). In this study, the DRH potential was calculated on monthly basis from January to December to elucidate the temporal variation of storage amount. The average monthly precipitation and the minimum amount of monthly precipitation were calculated for each grid cell (of precipitation data at 0.05° resolution) for each month from January to December based on the 35 years climatology.

As the study is primarily based on precipitation, it is also useful to check the long term trend in precipitation and its statistical significance. Long term trend in annual precipitation from 1981 to 2015 with 95% significance level ($\alpha = 0.05$) was calculated by fitting a linear model to the annual cell average precipitation of total study area. Long term trend in annual precipitation of each grid cell was calculated using same procedure to demonstrate the spatial distribution of trend.

3.2. Roof area calculation

Roof surface is the catchment area used for DRH system in this study. Approximating roof area thus plays a pivotal role in designing the system. The housing pattern of one region can be significantly different from another. In this study, the whole study region was segmented into 13 sub regions in order to account for the variation of housing pattern. The sub regions and the roof samples are showed in Fig. 3. In each region, at least 30 roof samples were taken to estimate the average roof area of that region.

The roof samples were reproduced by drawing polygons covering the roof as shown in the inset map of Fig. 3. The polygons were then imported in ArcGIS and re-projected to projected coordinate system WGS 1984 UTM zone 45N to calculate the area of the individual roof sample. Table 1 shows the average household roof area and number of roof samples taken in each region.

3.3. Storage calculation

All the calculations in this section and the next section were done for individual grid cells. As a conservative measure, each month's minimum harvestable rainwater was used in designing the DRH system. The decisions derived using this procedure will be more compelling and robust. Monthly harvestable rainwater Q_L for each month was calculated for each grid cell using the following equation.

$$Q_L = R_{min} \times A \times \beta \times C \tag{1}$$

R_{min} is the minimum monthly precipitation of that particular month during last 35 years, A is the average roof area of the specific region where the grid cell is located, β is the percentage of roof area utilized for rainwater harvesting and C is the roof runoff coefficient. The value of β is taken as 0.35 suggested by Shittu et al. (2015). Roof runoff coefficient was taken as 0.8 used by Otti and Ezenwaji (2013), Balogun et al. (2016) and Shittu et al. (2015). The annual harvestable rainwater was calculated by adding up the monthly harvestable rainwater from January to December.

The storage amount at the end of each month was calculated using simple mass balance equation for different combinations of reservoir size and water demand. The model was developed by assuming a 6 person family of two parents and four children.

Mass balance equation used in this study, $S_n = I_n - O_n + S_{n-1}$, $0 \le S_n \le R$ (3)

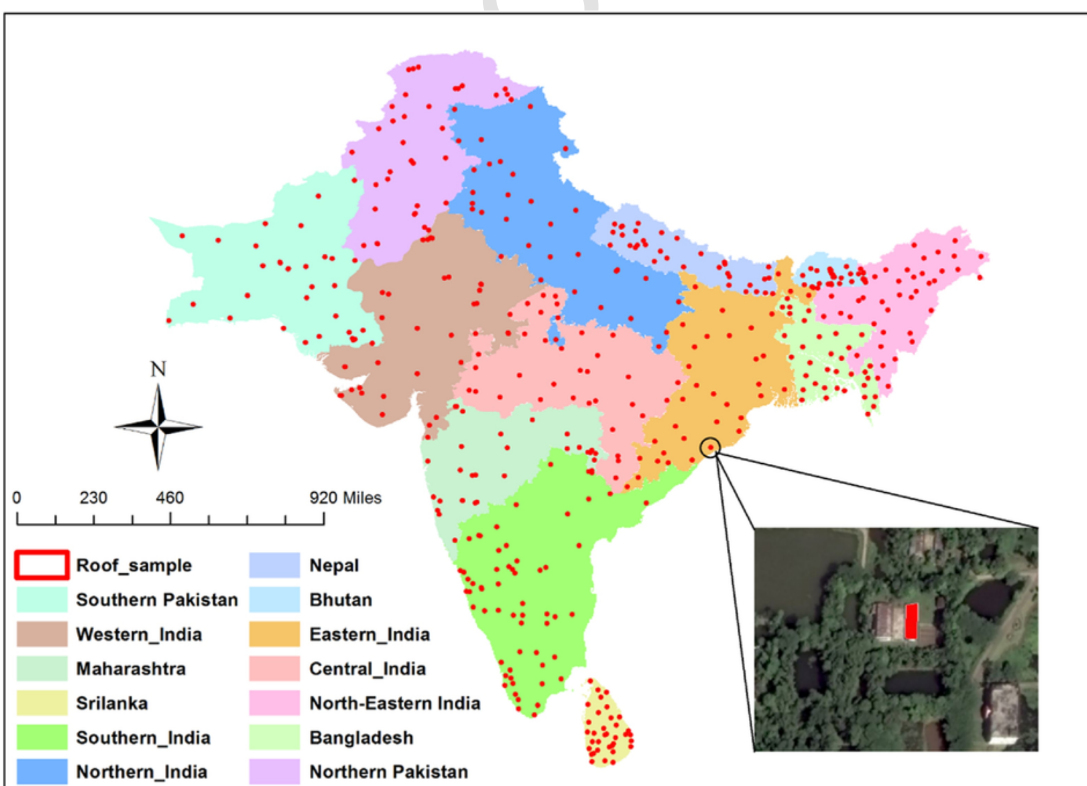

Fig. 3. Roof area samples in different regions of South Asia derived from visible satellite imagery via Google Earth.

Table 1
Number of roof samples and average roof area in each region of South Asia.

Zone	Average Roof area (m^2)	Number of samples
Northern India	127.633	34
Western India	97.7	37
Central India	113.81785	35
Maharashtra	105.5	33
Southern India	147.524	58
Eastern India	106.527	35
North-Eastern India	124.55	40
Srilanka	157.57	35
Bangladesh	95.38	35
Northern Pakistan	126.3	36
Southern Pakistan	108.7	36
Nepal	94.243	35
Bhutan	132.694	33

Where Sn = storage amount at the end of the month, I_n = inflow in the reservoir (lower bound of monthly harvestable rainwater of month n), O_n = Outflow from the reservoir (amount of water required for a 6 person family for month n), S_{n-1} = storage amount at the end of previous month and R is the reservoir size.

In most places of the study area, precipitation is minimum during the dry season from November to March. It is expected that storage would be minimum at the end of March. The tank should be emptied and cleaned properly at the end of the March to ensure water quality for the following year of rain harvest. The equation 3 was iterated from April to March to calculate the storage amount in the reservoir at the end of each month.

Two types of demand were considered in this study as recommended by World Health Organization (WHO). The analysis was done for 6 different combinations of tank (reservoir) sizes that are considered reasonable to build and maintain in a rural environment. These are listed below (Table 2).

Combination 1: 2m*2m*1 m (4 m^3) reservoir to fulfill potable water demand

Combination 2: 2m*2m*1 m (4 m^3) reservoir to fulfill domestic water demand

Combination 3: 3m*2m*1 m (6 m^3) reservoir to fulfill potable water demand

Combination 4: 3m*2m*1 m (6 m^3) reservoir to fulfill domestic water demand

Combination 5: 2m*2m*2 m (8 m^3) reservoir to fulfill potable water demand

Combination 6: 2m*2m*2 m (8 m^3) reservoir to fulfill domestic water demand

Table 2
Different water demand.

	Application	Amount (per capita per day)	References
Potable water demand	Drinking and Cooking	7.5 liters	World Health Organization (2004), World Health Organization (2005)
Domestic water demand	Drinking + Cooking + Basic hygiene needs + Basic food hygiene	20 liters	World Health Organization (2016)

3.4. Percent of the time of the year water demand satisfied

Percent of time of the year potable and domestic water demand is fulfilled were calculated using the average annual harvestable rainwater. This represents the percent of time of the year water demand can be fulfilled if there are no storage limitations.

In this study, percent of time of the year water demand would be fulfilled was also calculated for six different combinations of tank sizes mentioned in the Section 3.3. First, the percent of time of each month water demand would be fulfilled was calculated by using the storage amount at the end of the previous month and minimum amount of monthly harvestable rainwater in that month.

Percent of time of each month water demand would be fulfilled,

$$P_n = 100*(I_n + S_{n-1})/O_n \quad (3)$$

This percent of the time of each month was then added and converted into the percent of the time of the year water demand would be fulfilled for those six combinations.

4. Result and discussion

4.1. Spatial and temporal distribution of rainfall

The South Asian region experiences substantial temporal and spatial variation of rainfall. Monthly precipitation (mm) climatology of different regions are presented in Fig. 4 to demonstrate both the temporal and spatial variation of rainfall. In almost all regions, the weather are typically dry during October to June. The Fig. 4 clearly depicts that amount of rainfall is significantly higher during July to September in most parts mainly due to summer monsoonal precipitation. The southern part of India and whole Sri Lanka receive significant amount of rainfall during October and November due to winter monsoon as shown in Fig. 4. The north-western part of South-Asia is dry and receives small amount of precipitation compare to the north-eastern part which enjoys the highest amount of rainfall.

4.2. Trend analysis

The long-term trend in annual precipitation from 1981 to 2015 was calculated by fitting the annual cell averaged precipitation of total study area into a linear model. The null hypothesis for the significance test was: Long term trend is zero. The alternate hypothesis was: The trend is not zero. The trend line is shown in Fig. 5.

The value of slope (mm/year) = 3.4. 95% confidence interval of slope (mm/year) = (0.9873, 5.8986). There is a positive trend of 3.4 ± 2.46 mm/year in annual precipitation. As there is no zero value within the 95% confidence interval, the trend is statistically significant at 95% confidence.

The long-term trend in each grid cell was then calculated by fitting the annual precipitation from 1981 to 2015 into a linear model. This provides a better perspective about the spatial distribution of long term trend in annual precipitation. The long-term trend in annual precipitation is either positive or statistically not significant in almost all the regions of South-Asia as shown in Fig. 6. Therefore, analyzing the domestic rainwater harvesting potential using present climate is a viable and reliable option for South-Asia region.

4.3. Potential amount of harvestable rainwater

Fig. 7 represents the potential amount of rainwater that can be harvested per rural household annually if there is no storage constraint. The amount varies significantly within the study area. The amount is particularly low (around 0–5 m^3) in most portions of Pakistan and

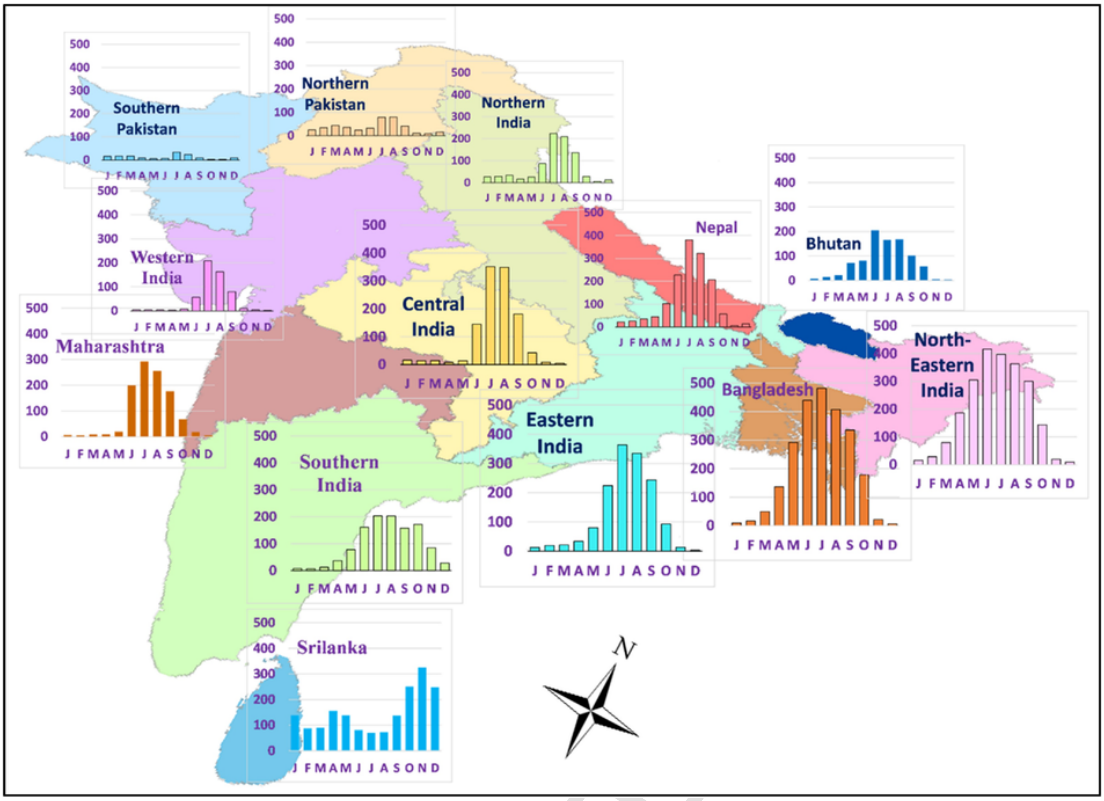

Fig. 4. Schematic Map of monthly Climatology of different regions in mm.

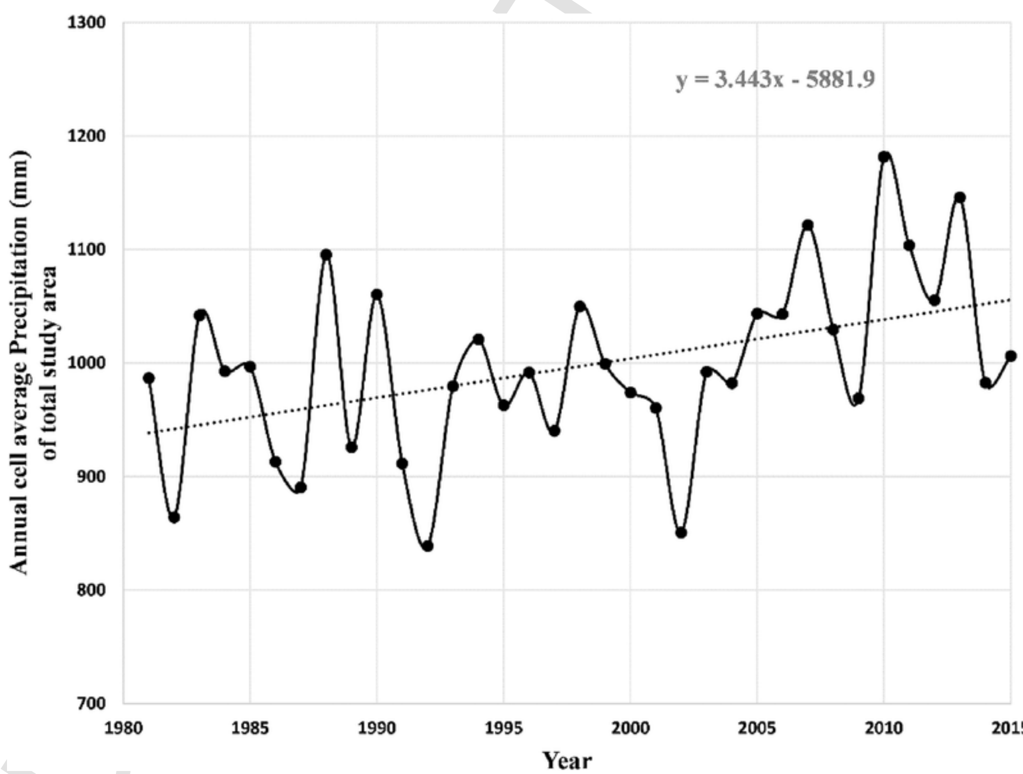

Fig. 5. Long term trend in annual cell average precipitation.

Western India. Large amount of rainwater can be harvested in North-Eastern part of India and Bangladesh. Households in coastal areas of South-Western India and Sri Lanka can store $25m^3$ to $90m^3$ rainwater annually. In Eastern, South-Eastern parts of India and great Himalayan range in the north of the study region, household can store $15m^3$ to $25m^3$ of rainwater annually.

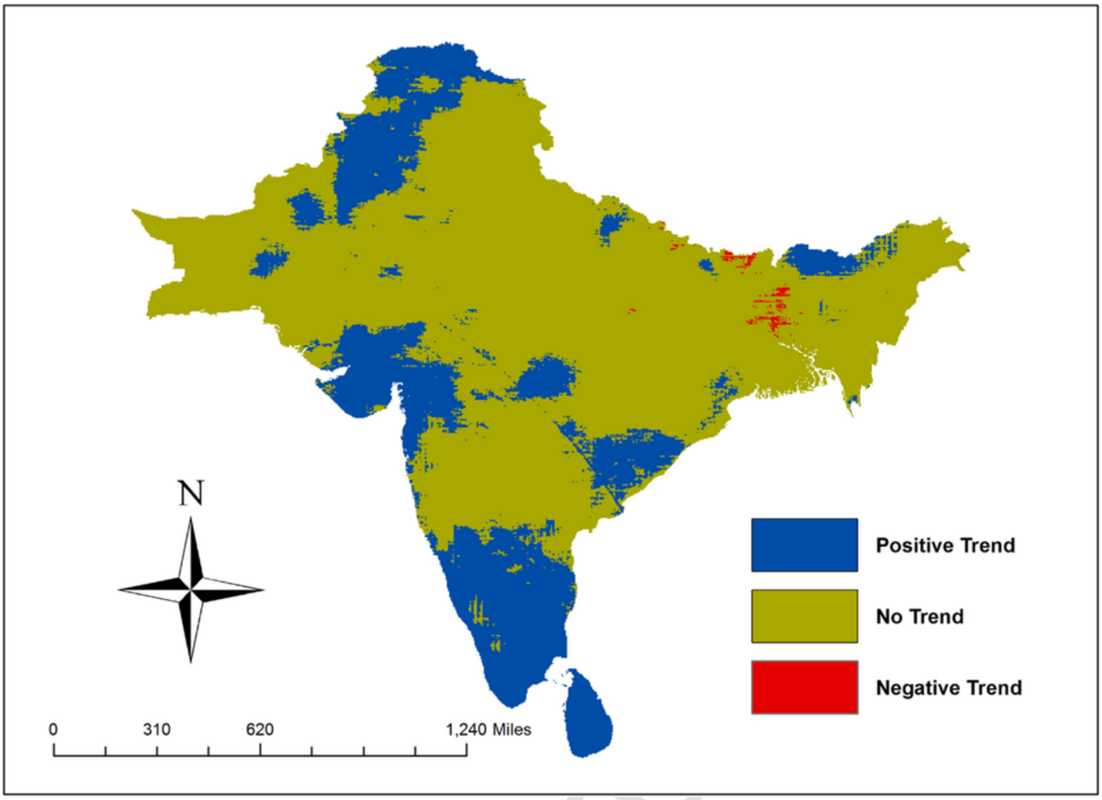

Fig. 6. Spatial distribution of long term trend in annual precipitation.

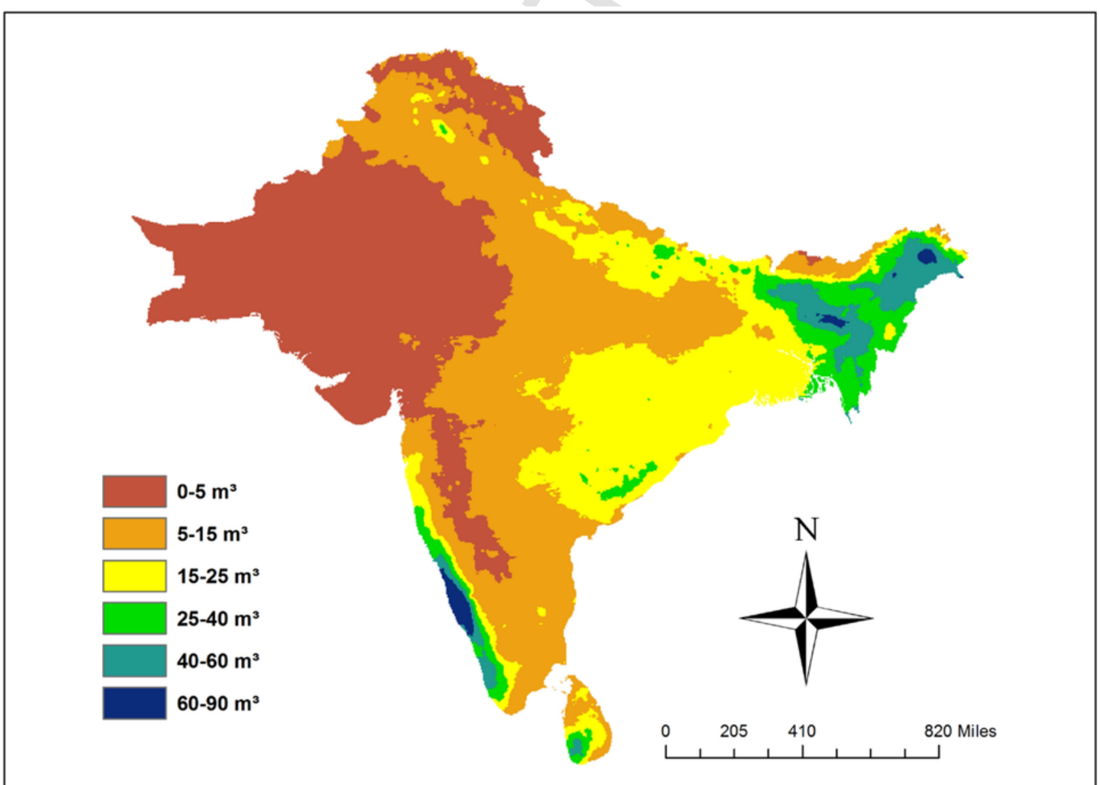

Fig. 7. Potential amount of rainwater that can be harvested annually per rural household assuming no storage limitation.

4.4. Water demand fulfilled without storage limitation

Fig. 8(a) and (b) represent the percent of time of the year potable and domestic water demand of a 6 person family can be fulfilled by the potential amount of annual harvestable rainwater, respectively. The lower percentages in all the parts of Pakistan, western and northern parts of India indicate that domestic rainwater harvesting is not a viable option in these regions for meeting potable and domestic water demands. In all other regions, potable water demand can be fulfilled comfortably if all the harvestable rainwater can be stored. Except North-Eastern part of India and Bangladesh, domestic rainwater harvesting will not be feasible for supplying sufficient domestic water despite storing all the harvestable rainwater as demonstrated in Fig. 8.

4.5. Demand fulfilled with storage limitation

Estimating the percent of time water demand fulfilled using monthly harvestable rainwater and considering storage constrain is a more realistic approach. It represents the real word scenario better as it considers the month to month variation of rainfall and reservoir size limitations within the context of dynamic water demand (or usage). Fig. 9(a) indicates that $4m^3$ reservoir tank would be enough to satisfy the potable water demand of a 6 persons family in dark blue portions (north-eastern India) of the map. 6 m^3 reservoir appears to be the preferred option in the coastal part of southern India, Srilanka and Bangladesh. However, at least $8m^3$ reservoir is required to satisfy the

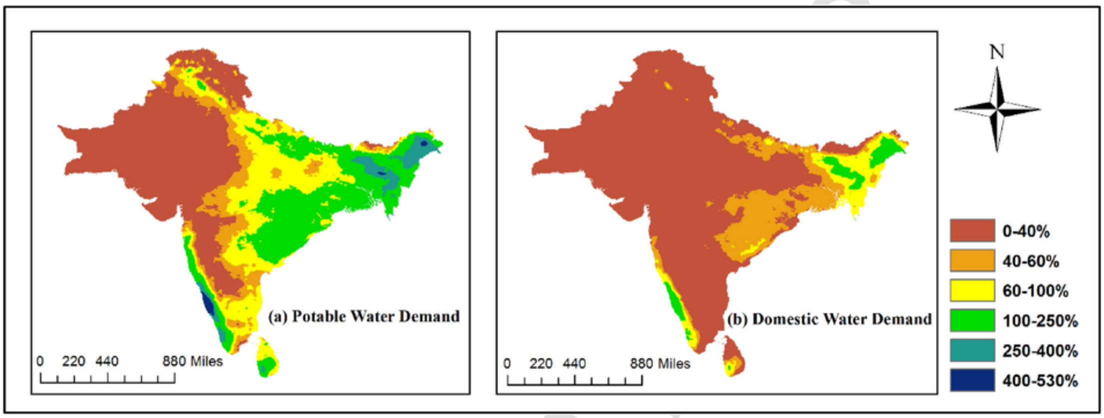

Fig. 8. Percent of time of the year a) Potable water demand b) Domestic water demand is fulfilled without storage limitation.

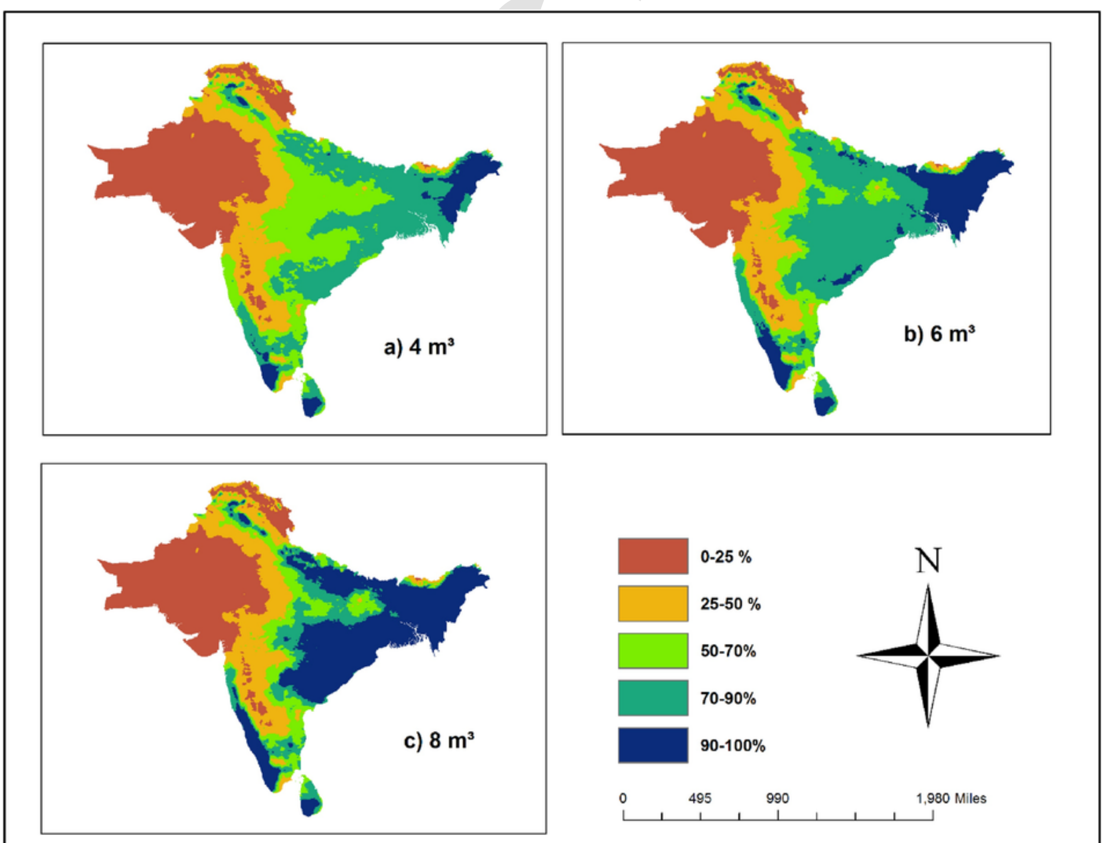

Fig. 9. Percent of time of the year potable water demand fulfilled with a) $4m^3$ b) $6m^3$ and c) $8m^3$ reservoir size.

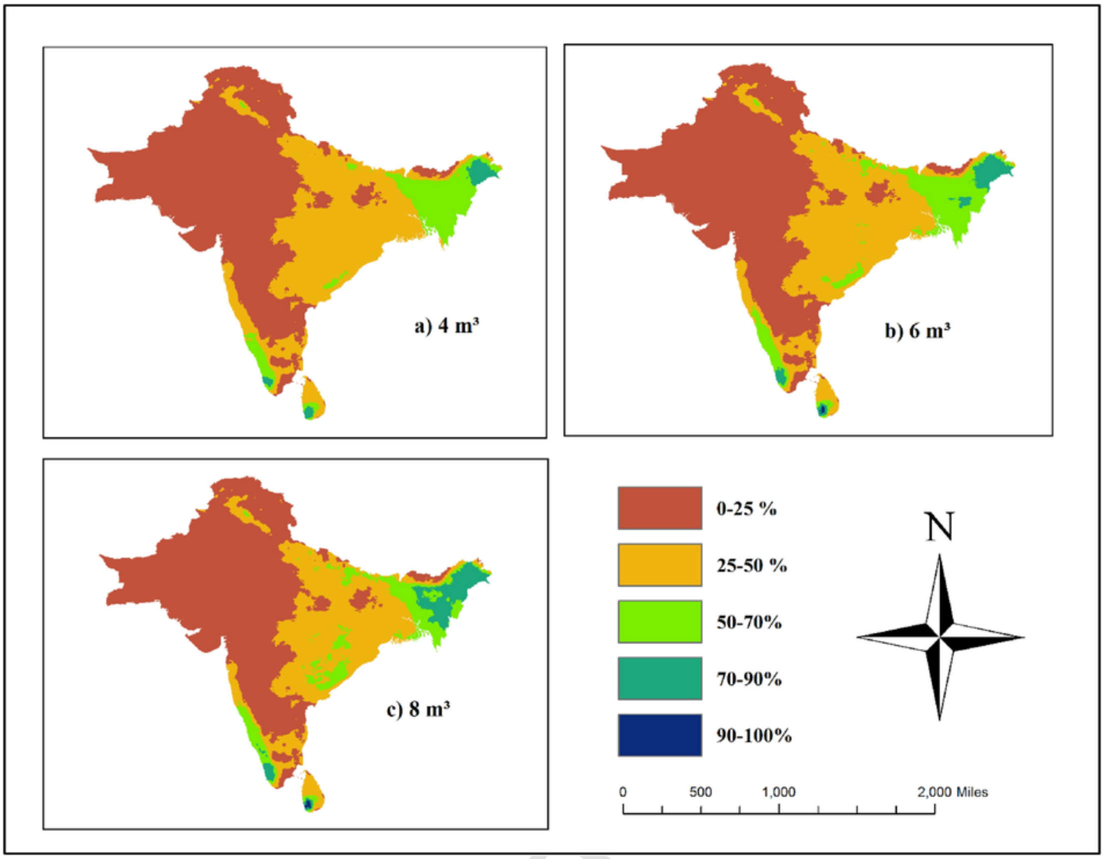

Fig. 10. Percent of time of the year domestic water demand fulfilled with a) $4m^3$ b) $6m^3$ and c) $8m^3$ reservoir size.

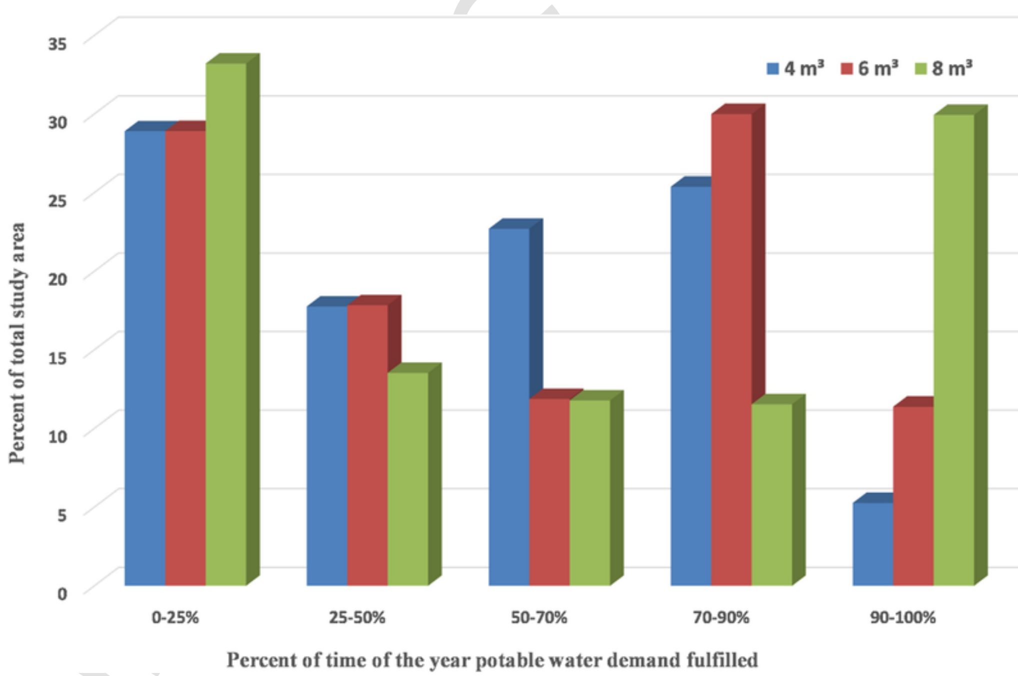

Fig. 11. Variation in area coverage of potable water demand with respect to different reservoir sizes.

potable water demand throughout the year in Eastern and Central India as shown in Fig. 9(b) and (c).

Fig. 10(a)–(c) represents the percent of time of the year domestic water demand (which includes potable water demand) is satisfied with $4m^3$, $6m^3$ and $8m^3$ reservoirs respectively. Other than some parts of southern India, Sri Lanka and northeastern India, DRH might not be able to supply domestic water throughout the year even with an $8m^3$ reservoir. The dark green regions in the map can supply domestic water for almost 70–90% percent of the year which is good enough to recommend DRH in those regions. Domestic rainwater harvesting can be

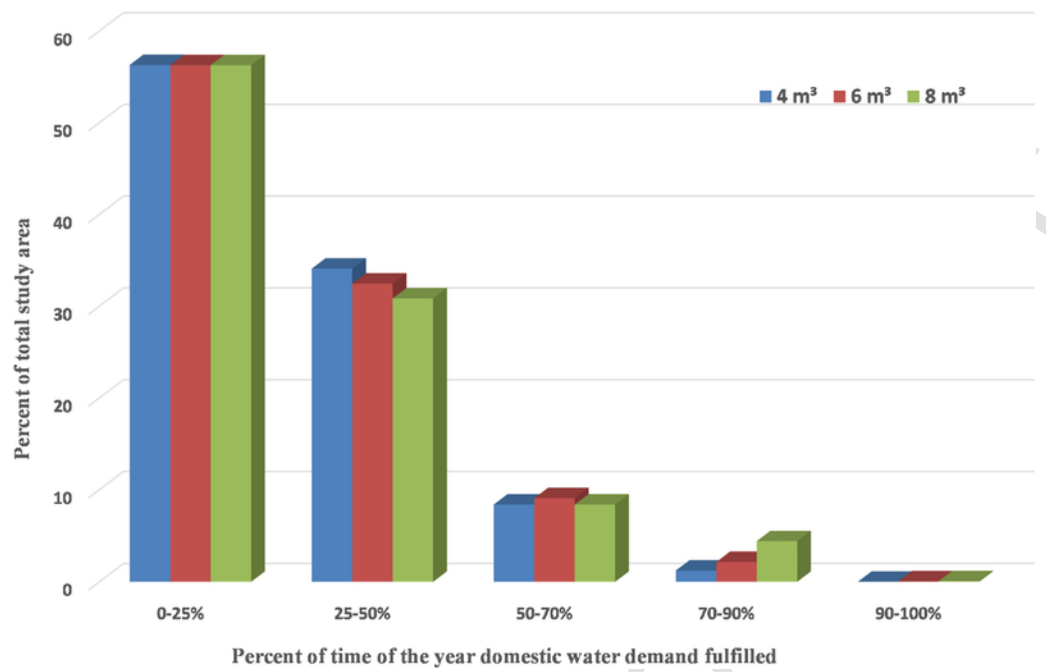

Fig. 12. Variation in area coverage of domestic water demand with respect to different reservoir sizes.

used as a supplementary source of domestic water in the regions indicated by the light green for 6–7 months of the year.

People can also utilize mixed use (Use 20 lpcd from storage during monsoon season and 7.5lpcd rest of the year) scheme to maximize the benefit from rainwater harvesting. The reliability of domestic rainwater harvesting system depends highly on climatic variability and can differ significantly from year to year (Imteaz et al., 2015). However, climatic variability has not been accounted in this study as the focus was used to assess the performance of rainwater harvesting during the worst-case scenario.

4.6. Effect of storage size on geographic coverage

Geographic coverage from different storage sizes were derived from Figs. 9 and 10. First, the areas with different ranges of time coverage (0–25%, 25–50%, 50–70%, 70–90%, 90–100%) were calculated for each storage size and demand combination which were converted to the percent of total study area. Figs. 11 and 12 represent the variation in areal coverage of potable and domestic water demand with respect to different reservoir sizes. Fig. 11 demonstrates that reservoir size does not have much impact in the regions where potable water demand satisfied less than 50% time of the year. However, Reservoir size can significantly increase time coverage in regions where potable water demand is satisfied for 50–90% time of the year.

In case of domestic water demand, percent of time water demand satisfied remains static in areas where water demand is fulfilled 0–25% time of the year. However, increasing the reservoir size improves the conditions in those areas where domestic water demand is fulfilled 25–90% of time of the year.

5. Conclusion

The pressure to meet the safe water demand and ensuring better public health is increasing with the rapid urbanization, climate change and population growth. A multi-disciplinary approach with efficient water management techniques are required to ensure the best use of available resources. Rainfall is one of the naturally available sources of water that is also of good quality and requires little energy for extraction (or harvest). Rainwater harvesting is therefore a low-energy or no-energy process that can be a lifeline for rural communities around the world due to its cost effectiveness. This rainwater can be used for drinking, cooking or basic hygiene purposes with simple point of use purification techniques. A rural water supply system based on rainwater harvesting can bring enormous public health benefit to the rural communities by reducing water related diseases and improving the overall standard of living.

In this study, the potential of rainwater harvesting in South Asia region was assessed using a comprehensive precipitation climatology dataset of 35 years. This study is particularly unique as it uses concepts of water balance to account for the month to month variability of the rain harvest in the context of water demand for a large region consisting several developing countries where rainfall occurrence is heavily skewed during the monsoon season. We see that there are vast regions of South Asia with untapped rainwater harvesting potential that should allow robust functioning even during droughts. This comprehensive analysis will assist the policy makers and engineers in South Asia to move forward with a region-specific guideline. For example, the study demonstrated that household in north-eastern India can fulfill the potable water demand throughout the year using a $4m^3$ reservoir. An $8m^3$ reservoir can satisfy the potable water demand in the most parts of South Asia. However, most regions of Pakistan, northern and western India are not rainwater harvest-friendly.

The results of this study do not represent the feasibility of the DRH in the urban areas due to greater population density in urban area under a much smaller roof top area. This study also did not consider the socio-economic or demographic information across South Asia. Fixed per capita water demand recommended by the World Health Organization (WHO) was used in this study. Yet, it is known that water demand can vary from place to place due to cultural and socio-economic factors. While the findings are representative of the 'now' climate, a similar kind of analysis needs to be explored in the context of climate change and other bottom-up stress factors to answer '*how relevant will rainwater harvesting be 50 years from now?*' We plan to address many of these issues and limitations in a future extension of this work.

Uncited reference

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