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Assessing the Potentiality of Rainwater Harvesting via Zoning in the Core City Limits of the Kathmandu Metropolitan City

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Abstract

Rapid and haphazard urbanization, alarming population growth, and climate change are causing a huge stress in water management in Kathmandu Metropolitan City (KMC). Declining ground water level, expanding water supply-demand gap, and increased intensity and frequency of urban flooding in the city are of major concern. Rainwater harvesting (RWH) is considered as a potential solution in addressing water stress and aiding water management in different parts of the world. This study explores the potential of RWH in urban context of KMC and delineate the potentiality index via zoning. Analytical hierarchy process (AHP) based multi-criteria decision making is applied establishing rainwater harvesting potentiality index (RWHPI). Drainage density, roof area density, basin slope, and runoff coefficient are considered for RWHPI. Results showed that 28.78% of the total basin area has good RWHPI, 46.30% has moderate, and only 24.90% has low RWHPI. Also, Roof Rainwater harvesting (R-RWH) is alone able to meet nearly 23% of the total domestic water demand of the city.

Keywords
Urban water management, hydrological modeling, Hec-HMS, Analytical Hierarchy Potential (AHP)

1. Introduction

The urban population growth rate in Nepal almost doubled from 3.6% in 1991 to 6.5% in 2001, and the number of urban centers increased from 58 in 2013 to 293 in 2017 [1]. Kathmandu Valley, home of the capital of the country and its largest city, has a population of nearly 2.5 million people, and is growing even further at an astonishing 6.5% per year. It is without a doubt one of the fastest growing metro areas in the South Asian region. The development however, has been completely haphazard. The unmanaged nature of the urbanization process has left the residents of the valley without basic necessities like water. According to the recent annual report 2021 published by Kathmandu Upatyaka Khanepani Limited (KUKL), the municipal water authority of the valley, the current water demand within Kathmandu Valley is 470 million liters per day (MLD), but its supply is as low as 91 MLD on average, creating a huge supply-demand gap. Groundwater from both shallow and deep aquifers (more than 200 metres) is being heavily extracted by small- to large-scale users, including KUKL itself. In the present situation, KUKL owns more than 107 operating deep tube wells (DTWs), 19 dug wells, 32 pumping stations [2]. Not just KUKL, most of the individual households have dug their own wells to meet their water demand. The unregulated extraction is depleting the aquifers, even in a situation where the deep aquifers available in the valley are not easily rechargeable due to the valley's impermeable black clay [3]. As of now, nearly 80% of the current demand in the valley can be met by groundwater [4]. However, the situation will not remain the same in the future. The water table level has been dropping in the past decades. Study on ground water environment has showed that urbanization, population growth along side increasing tourism has caused a huge gap in ground water extraction and recharge [5]. This had a decline in ground water level by 1.38–7.5 m during 2000–2008 [5]. It is absolutely critical that we monitor water levels regularly underground, and find ways to recharge the water table.

Figure 1: Floods in the streets during monsoon season is typical in Kathmandu (The Himalayan Times 2017).

While there exists a significant deficit in domestic water supply in Kathmandu Valley and in the Kathmandu Metropolitan City (KMC), there also exists a serious problem of water surplus due to constant rains during the monsoon season. Urban flooding is serious challenge that the residents of Kathmandu Valley face as a whole, but more specifically the residents of KMC. Specially for rapidly growing cities of developing countries, like Kathmandu, the problems of water management is more intense and urgent [6]. Kathmandu is in serious threat of urban flooding due every year to its striking rate of urbanization and growth. While the construction of the sewerage system in the Kathmandu valley started around 1920s, and the original drainage system in Kathmandu valley was designed for 200,000 people [7], the population growth and haphazard urbanization have been very high, and the existing drainage system in the valley overwhelms the system. The ground surface imperviousness in KMC has shown sharp increment of 9.5% to 18.71% in 1990, 37.35% in 2000 and 73.67% in 2010 [8]. Increased imperviousness of the KMC with urbanization and the inadequate drainage system has led to the occurrence of urban flooding, an example of which is shown in Fig. 1. It has been more frequent in Kathmandu valley during heavy rainfall events [9]. Extreme precipitation due to climate change and global warming is attributed as the main cause behind the increased frequency of floods [10]. According to a recent study, the precipitation in the Bagmati basin will follow an increasing trend of 2.9 mm/year and 4.97 mm/year in two different respective scenarios of Representative Concentration Pathways (RCP) under climate change, namely RCP4.5 and RCP8.5 [11]. Harvesting of the rainwater can be one potential solution to both the water crisis. Rainwater harvesting (RWH) is the collection of the rain that falls, and the thus collected rainwater can be used for potential solutions to our problems.

Rainwater has been used for various purposes all over the world, from drinking, to irrigation, to domestic use, to industrial use [12, 13]. In South Australia, 42% of its' population drink rainwater. In Bangladesh, rainwater is a major alternative source of drinking water in arsenic-affected areas. In Gansu Province of China, the annual precipitation of 300 mm is able to cater to 2 million people and supplies supplementary irrigation for 236,400 hectares of land. At Singapore's Changi Airport, 63,500 tonnes of rainwater is used for flushing toilets and cooling the terminal buildings each month, which constitutes about 33% of the total water used, that results in monetary savings of approximately USD 390,000 a year. In India, direct recharge of rainwater into the ground resulted in groundwater level increases of up to 5 to 10 metres in just two years [14]. While there's little to no hope of reversing the urbanization and the changing climate to extremes, best that could be done is to adapt with the situation implementing RWH to address the problem of water scarcity and urban flooding. Given such successes around the world, it is clear that rainwater harvesting has a high potential to address the water crisis in many of the world's urban areas. Thus, this study involves studying the possibility of rainwater harvesting in an ever growing urban unit KMC. The findings of the study might be helpful in giving RWH the importance that it deserves among the local population and concerned authorities in the present context because of its potential in solving the two main problems involving water management.

2. Methods

2.1 Digital Elevation Model

A digital elevation model (DEM) is a digital representation of any area that includes the elevation information of a given area. For this study, we obtained the DEM data from the United States Geological Survey (USGS). The DEM acquired from USGS had a resolution of 30 m x 30 m. DEM is used in a geograpical information system (GIS) software, ArcGIS®, to prepare a hydrological model using the software HEC-HMS (described below in Sec. 2.3), and to obtain the drainage density and basin slope of the study area.

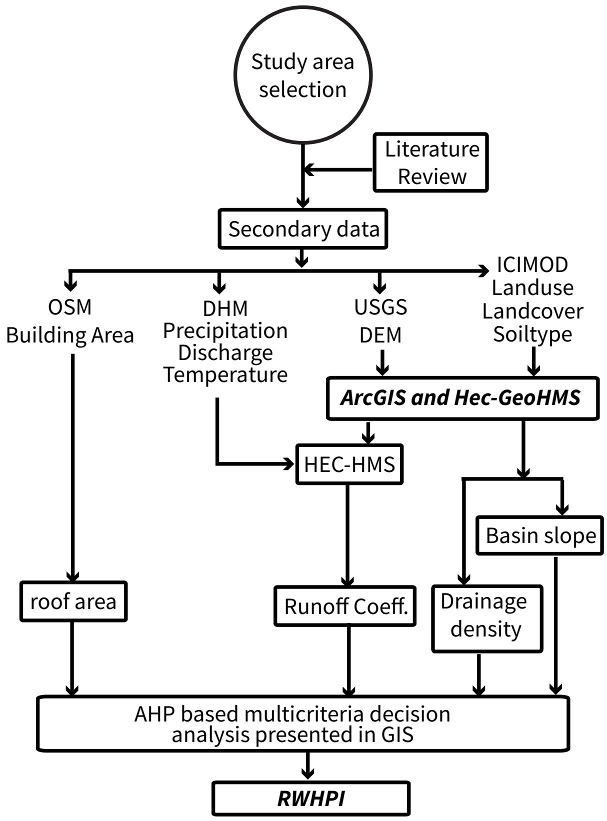

Figure 2: A flow chart of the methods for the study.

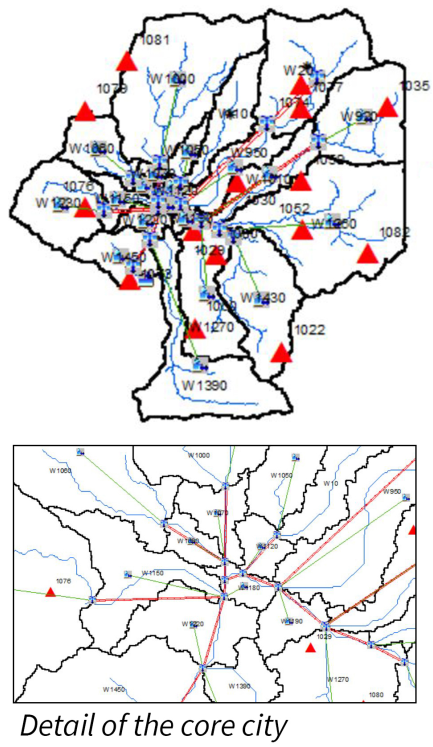

Figure 3: HEC-HMS model setup, with the inset showing the detail of the core city limits.

2.2 Hydrological data

Precipitation and discharge data for the Kathmandu Valley were obtained from the Department of Hydrology and Meteorology (DHM) of the Government of Nepal. For this study, precipitation data from 23 different stations within the Bagmati river basin was accounted, and discharge at Khokana outlet was taken, which is the main outlet for water from the valley. To account for the better spatial distribution of precipitation in the study area, Thiessen polygon method was followed. Precipitation distribution was obtained as area weighted factor of different precipitation stations in the study area. Also, to take the average temperatures of the basin, the centrally located Tribhuwan International Airport station was taken under consideration. The DHM data are used for hydrological modelling of the basin to get the estimate of runoff coefficient.

2.3 Model Setup

Hydrologic Engineering Center–Hydrologic Modeling System (HEC-HMS) v4.6 model was selected for this study. The DEM used as a secondary raster data was derived from USGS. Then the DEM was processed for a number of steps using Arc hydro tool.The threshold value used in stream grid development during ARC-hydro analysis tool was 4 km ^{2}.
Then, further processing was done in HEC-geoHMS 10.8 to prepare the final hydrological model input required for HEC-HMS. The merging of sub basins were needed and done in a way that the the KMC limit had possible maximum numbers of sub-basins required for zoning. Total 25 Sub-basins were formed, 15 of them were either fully or partially under our study area, KMC.

The above steps finally allow extraction of basin characteristics, and generation of topographic characteristics of streams and sub-basins, including stream line length, stream line slope, basin slope, longest flow path, basin centroid (using center of gravity method), basin centroid elevation, and centroidal longest flow path.

The basin model prepared in HEC-geoHMS was imported into the HEC-HMS v4.6 environment. Baseflow, canopy, and surface was carried out by recession, simple canopy, and simple surface method respectively. Initialization of these parameters were derived from Ref. [10] for Bagmati river basin. For generating and calculating basin wise average curve number (*CN*), the available latest land use and soil map data were used from ICIMOD [15]. Soil Conservation Service (SCS) curve number and the SCS unit hydrograph methods were used for calculating sub-basin loss and transform respectively. Transform method lag time was calculated as from the following equation [16]:

$$Lagtime(hour) = \frac{2.587 \times L^{0.8} \times (\frac{1000}{CN} - 9)^{0.7}}{1900 \times H^{0.5}}. \quad (1)$$

where L is the hydraulic length of watershed, CN is the curve number, and H is the average slope of watershed.

In reach routing method, the lag time was calculated as[16]:

$$Lagtime(hour) = \frac{l^{0.65}}{83.4} \quad (2)$$

where l is the hydraulic length in meters.

Basin slope, river length were obtained from HEC-GeoHMS model for the basin, and then the drainage density for each basin is calculated. The runoff coefficient will be acquired from HEC-HMS model once the model is optimized for required performance level.

2.4 Roof area calculation

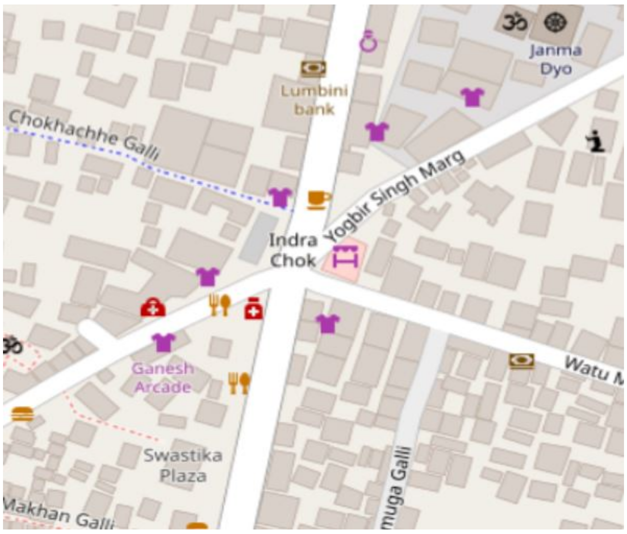

Figure 4: Sample shot of OSM map that shows how rooftops are visualized in the system.

The fourth major part of the study data is obtained from Open Street Map (OSM). This study is focused in Rainwater harvesting in urban setting. In the city area, a large chunk of the actual area has buildings. And so, the roof area of the buildings become significant in determining the potential of rainwater harvesting. The most detailed and accurate way to get the rooftop area of given buildings would be to get individual building's municipal drawings, however that is extremely impractical due to the potential of time investment required, as well as legitimate privacy and safety concerns of the building owners. Instead, OSM output are used for this study. Specially for a developing country like Nepal, and for projects that do not have any fundings, open source alternatives to any software or service is a great, and encouraging solution.

Open Street Map provides satellite imagery based building profiles, an example of which is shown in Fig. 4. Even in one of the densest regions of the entire country, Indra Chowk, the buildings are clearly defined.

2.5 Multi-criteria decision analysis

Analytic Hierarchy Process (AHP) was used in the study, which involves multicriteria decision analysis as described by Saaty in 1980 [17]. The analysis was carried out for rainwater harvesting (RWH) potential zones identification with respective potential index in KMC. Four factors considered for this study were: basin slope, drainage density, runoff coefficient, and roof area. Determination of the weight assignment for different criteria and their associated features, on a 1-9 scale suggested by Saaty [17] were made based on available literature on similar studies [18, 19]. Then the assigned weights were normalized by the eigenvector technique and examined for consistency ratio. Consistency ratio below 10% was opted.

The following approach was used for calculating the RWHPI,

$$\begin{aligned} RWHPI = &(RC)_f(RC)_c + (DD)_f(DD)_c \\ &+ S_fS_c + (RA)_f(RA)_c \end{aligned} \quad (3)$$

Where,

$RWHPI$ = 'Rainwater Harvesting Potential Index' for a sub-basin.
RC_c = normalized weight of the runoff coefficient criteria.
RC_f = normalized weight of a feature of the runoff coefficient criteria.
DD_c = normalized weight of the drainage density

criteria.
DD_f = normalized weight of a feature of the drainage density criteria.
S_c = normalized weight of the slope criteria.
S_f = normalized weight of a feature of the slope criteria.
RA_c = normalized weight of the roof area criteria.
RA_f = normalized weight of a feature of the roof area criteria.

2.6 Quantity runoff from roof catchments

Runoff from roof catchment is a function of the precipitation and the runoff coefficient of the roof. Roof catchments can be of a wide variety depending on the design of the roof. In urban context of Nepal majority of roofs are cemented but there is a non-trivial proportion of corrugated sheets, and more recently, tiles. Thus, runoff coefficient for the roofs will vary accordingly. Since it was not practical to do the actual field survey to asses information, a study on the relevant topic was referred, where a sample survey was done for Ward 9 of KMC [20]. It showed that 85 percentage of the total houses had cemented roof, 13 percentage had tiles and only 3 percentage had corrugated sheet [20]. The runoff coefficient for roof catchment in the present study was scaled by the weighted average method from the study referenced. Runoff coefficient for cemented roof, tiles and corrugated sheet was found to be 80, 85, and 75 respectively [21]. The runoff quantity is calculated using average precipitation in the roof area and runoff coefficient by the equation:

$$R_v = \frac{A \times C \times P_v}{1000} \tag{4}$$

where,
C= runoff coefficient
R_v= Runoff volume (m^3)
P_v= Precipitation (mm)
A = Catchment area(m^2)

3. Results

3.1 Roof areas

Using OSM, we first computed the total roof area within KMC. The roof areas, segregated by the different sub-basins with color, is showin in Fig. 5. The figure clearly shows the rivers that flow through the city.

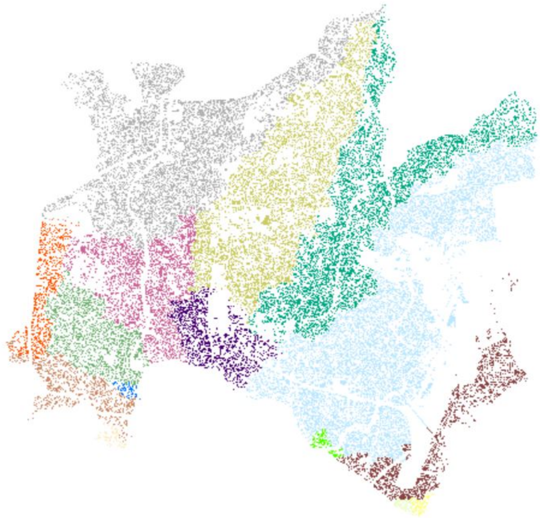

Figure 5: Computed roof areas using OSM for the study.

3.2 Model performance

To get the estimate of basin wise runoff coefficient, rainfall runoff modelling was done in HEC-HMS.Calibration of the model was done for the year 2000-2002 and validation was done for the year 2003-2007 using daily data for discharge at Khokana outlet. To evaluate the model performance, Nash Sutcliff Efficiency (NSE), Percent Bias (PBIAS), and coefficient of determination (R^2) of the best-fit line of observed and modeled discharge plot were used. The model performance evaluation criteria is summarised in the Table1 which is based on [22].

Figure.6 and fgiure.7 shows the plot of observed and simulated discharge at the Khokana outlet for the period of year 2000-2007 for daily data and monthly data. The model had the NSE of 73.3% and 52% for calibration and validation respectively. The cumulative volume of observed and simulated discharge for calibration period was -8.48% i.e simulated discharge volume low by 8.48%, while in validation the simulated cumulative volume exceeded the observed cumulative volume by 3.63 The R^2 value for for calibration and validation were 0.744 and 0.741 respectively. Similarly, the model Performance evaluation criteria for monthly discharge showed that the model is able to simulate the discharge with NSE of 84.2% and 79% for calibration and validation respectively. While discharge volume was under predicted by model in calibration by 8.48% and slightly over predicted i.e 1.38% invalidation years (2003-2007). The coefficient of determination, R^2 was

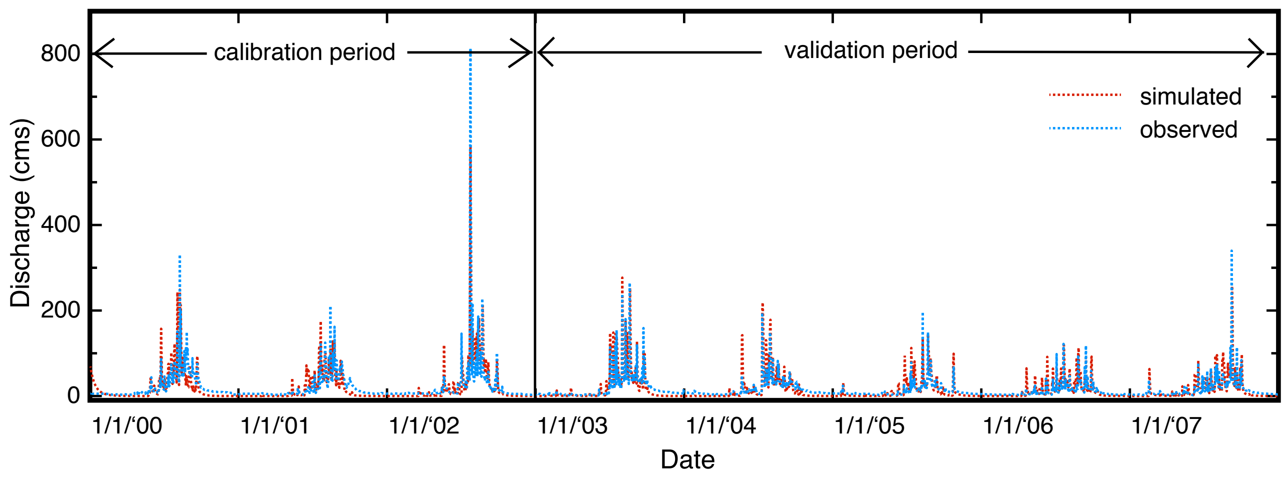

Figure 6: Daily Observed vs simulated data for Khokana.

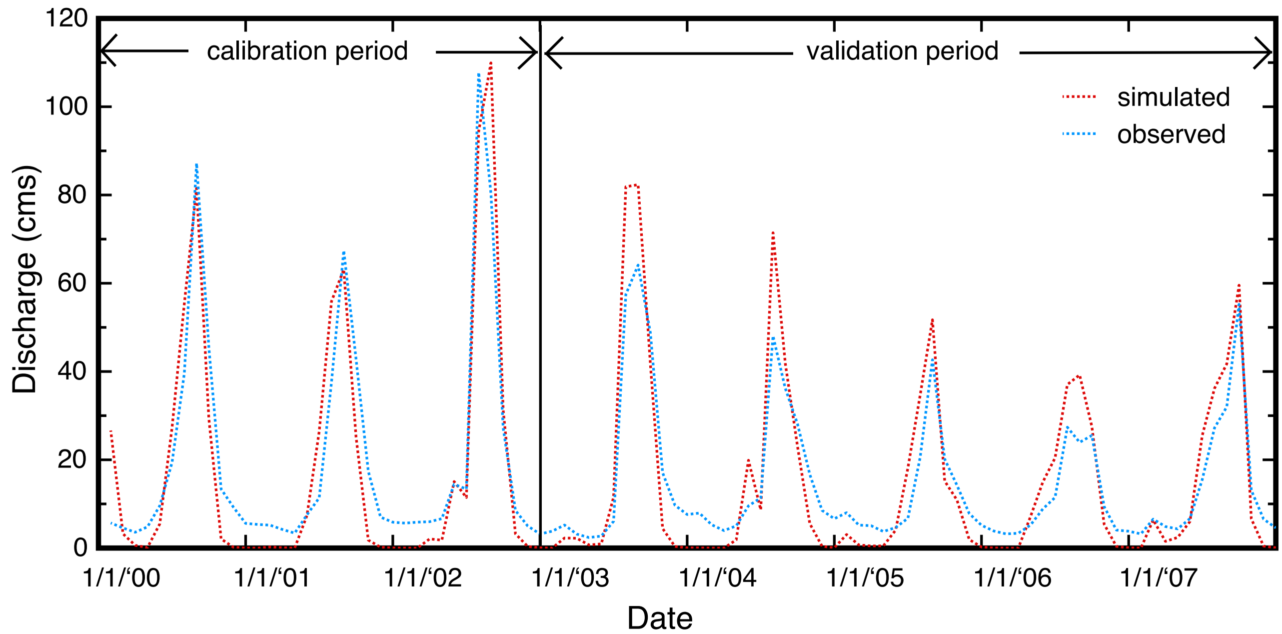

Figure 7: Monthly Observed vs simulated data for Khokana.

found to be 0.876 and 0.9 in calibration and validation respectively.

Criteria		Calibration	validation	overall
		(2000-2002)	(2003-2007)	(2000-2007)
PBIAS	D	-8.4	3.62	-3.05
	M	-8.49	1.38	-3.299
R-square	D	0.744	0.741	0.725
	M	0.876	0.900	0.875
NSE	D	0.733	0.52	0.676
	M	0.842	0.79	0.865

Table 1: Model performance categorization. D stands for daily, and M stands for monthly data.

Table 1 shows the summary of the performance of the model, and its subsequent characterization based on Ref. [22]. The model for was simulated for the year 2000-2007 to get the estimate of runoff coefficient for this study. The overall model performance was found to be very good in terms of PBIAS and satisfactory considering NSE and R^2 for daily data. Also, on taking the average for monthly discharge data for both observed and simulated data, the performance of the model in terms of monthly data were better than the daily scale. Overall, the performance for monthly scale was found good.

Basin wise daily precipitation (derived using Thiessen polygon) of 8 years was used as rainfall input while simulated runoff from each basin from HEC-HMS model was used as runoff for the same period to get the respective runoff coefficients. The total annual runoff volume for KMC from the estimates of runoff coefficient from the model was found as 44,014,878 m^3, taking average precipitation for year 2000-2007.

3.3 Rainwater harvesting potentiality index

Rainwater harvesting potentiality index is the function of four basin characteristics–average basin slope, runoff coefficient, drainage density, and roof area. The summary of these characteristics are as shown in the Fig. 8.

The details of average basin slope of sub basins within KMC is shown in Fig. 8a. The slope ranged from 4.9% to 33%. Sub-basins W820 and W1060 had the highest average basin slope while most of the basins at the central area in the vicinity of Bagmati river had mild to average slope. The details of average drainage density of the sub-basins, ranging from 0.0003 m/m^2 to 0.0018 m/m^2, are shown in Fig. 8b. The basins with higher drainage density values lies around the Bagmati river. The runoff coefficients, shown in Fig. 8c, ranged from 0.40-0.66. Sub-basins W1140, W1150, W1090, W1070, W1050, W850, W1010, and W1190 has the higher runoff coefficient values than the rest. It is also the most important parameter among the four. The last parameter is the roof area density in percentage, shown in Fig.8d, which ranged from 10-42 percentage. Nine out of 15 sub-basins has the roof area above 30%, and only 2 out of 15 has the roof coverage below 20%.

Criteria	Features	Normalized weight
Runoff coefficient		0.70
	0.40-0.50	0.07
	0.50-0.55	0.15
	0.55-0.60	0.30
	0.60-0.66	0.48
Drainage Density		0.13
(m/m^2 10^{-3})	0.30-0.40	0.08
	0.40-0.50	0.15
	0.50-0.70	0.31
	0.70-1.88	0.46
Slope (%)		0.04
	4.9-6.0	0.42
	6.0-10.0	0.33
	10.0-20.0	0.02
	>20.0	0.08
Roof density (%)		0.13
	<11	0.06
	11-20	0.13
	20-30	0.19
	30-35	0.25
	35-43	0.38

Table 2: Weights of selected criteria and their features

Depending upon these factors and the provided weights to their their features as per Saaty [17], Rainwater Harvesting Potential Index was calculated using Eq. 3. The detail of the weights and criteria are summarized in Table 2. The RWHPI of the present study area ranged from 0.086 to 0.470. It was further broadly classified into three classes by in ArcGIS®, categorizing the value ranges 0.086-0.250 as low; 0.250-0.390 as moderate; and 0.390-0.470 as good potential index. From Fig. 9, it is clearly seen that vast majority of the basin is well suited for rainwater harvesting, as most of the region has either moderate, or good potential index for RWHPI. Six out of 15 basins comprising of 28% of the total basin area, i.e 14.23 km^2, was found to have good RWHPI. Then it is moderate RWHPI with 4 sub basins having 46.30% of the total basin area, while 24.90% of the KMC has low RWHPI.

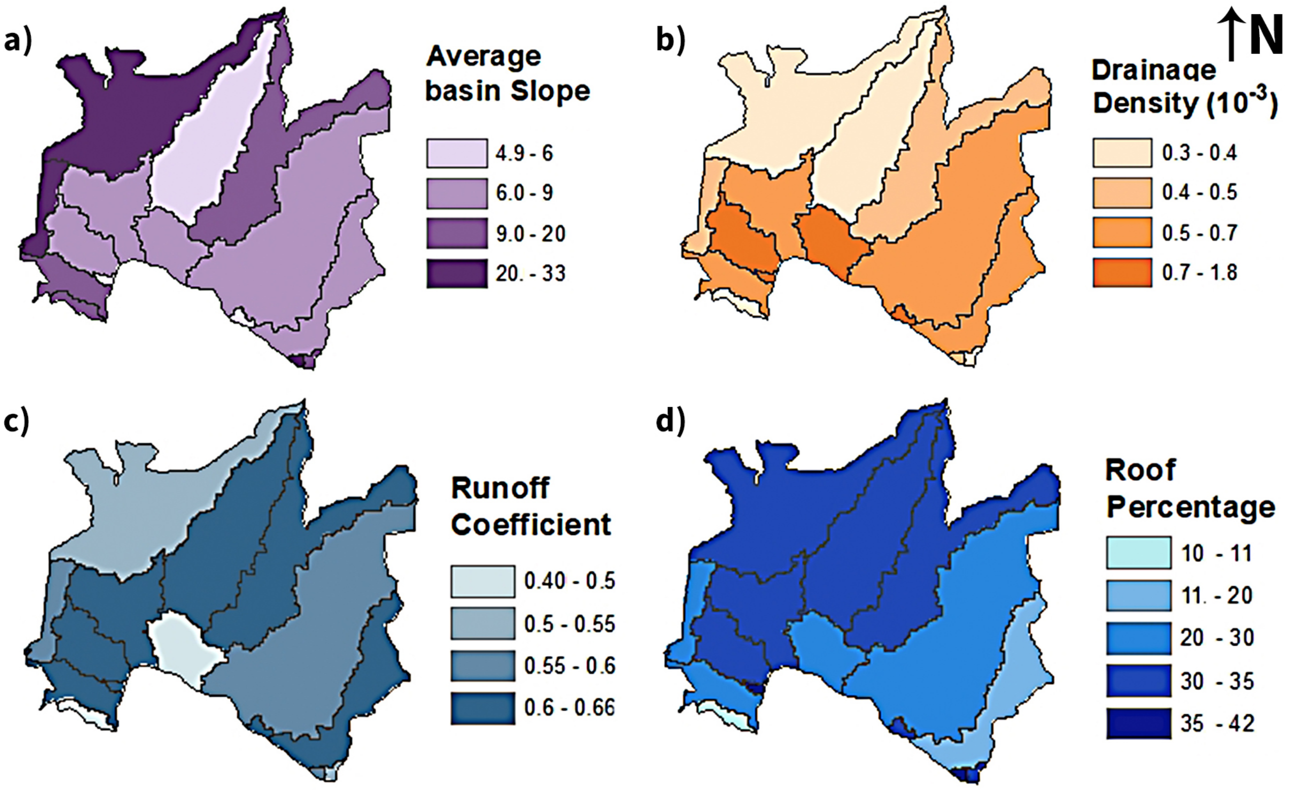

Figure 8: Figure showing (a) average basin slope, (b) Drainage density in m/m^2, (c) computed runoff coefficient, and (d) roof area percentage.

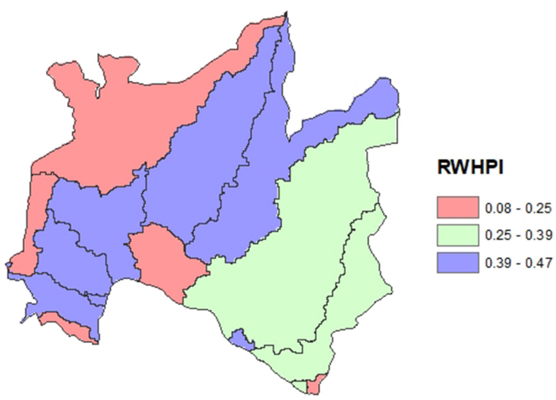

Figure 9: Figure showing rainwater harvesting potentiality index.

3.4 Quantity runoff from roof catchments

Roof areas are one of the major catchments for RWH in urban context or cities. On average buildings alone covered 30% of the total area of KMC. The average runoff coefficient of the roof catchment was obtained as 0.813 as discussed in section 2.6. The calculated average runoff volume via roof catchment using Eq.4 within KMC resulted in 51 MLD, while the overall demand of Kathmandu valley is 470 MLD. The 2020 population of Kathmandu valley is estimated to be 3,059,466 [23], and 1,424,000 for KMC alone [24]. Considering that the demand and population have a linear relation, the demand within KMC was found to be 218 MLD. Thus, RWH from roof of KMC alone is able to cover 22.9% of total domestic water demand. While rainwater harvesting is not just limited with roof RWH. The capacity of RWH will further increase if RWH is done on other surfaces like lawn, parking, roads etc.

Proper harvesting of water means better utilization of rainwater. Rainwater can be used for meeting the domestic as well as for recharging ground water through shallow wells.What this directly leads to is less runoff of rainwater into the streets. This would ultimately result in less urban flooding as well.

4. Conclusions

Kathmandu Metropolitan city is already under stress of huge water demand deficit. The water supply from KUKL is below 20% of the demand. Even if Melamchi Drinking water project is implemented successfully in future it will not be able to fulfill the gap and still leave a huge space to be filled. Residents of KMC rely on alternative sources of water, the major one being ground water. The extraction amount of groundwater is very high, which is accompanied by lower recharge due to growing urbanization. The situation is only growing worse. In addition to this, KMC is also facing increased monsoon flooding both in terms of frequency and magnitude, further enhanced due to urbanization and climate change.

In this study, the potentiality of rainwater harvesting was studied as a solution to solving both the problems. ArcGIS®, Open Street Map, and HEC-HMS were major tools used in this study. Ultimatelty, the potential was assessed with Rainwater Harvesting Potential Index (RWHPI).

Kathmandu Metropolitan City was divided into various zones, depending on basin modelling. The RWHPI for each sub-basin was computed with same zone. It was found that the majority of area, 75.1%, in KMC has moderate to good potential index for rainwater harvesting. Only a small area of KMC from this study 24.9%, has low RWHPI. This result is very positive as the majority of the area shows good potentiality of RWH. Furthurmore, upon considering the roof area for RWH, it showed that the it could supply 51 MLD domestic water to supplement the lacking supply from KUKL of 91 MLD from the municipal source, which goes a long way to meet the total demand of 218 MLD within KMC. It would also help in ground water recharge. The total annual runoff volume for KMC from the estimates of runoff coefficient from the model was found as 44,014,878 m^3, which is consistent with the data found in literature within 10% [25].

The thus collected rainwater would also prevent it from being drained into the streets, which would help alleviate the issues of urban floods in the city.

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