A water balance approach to assess rainwater availability potential in urban areas: the case of Beijing, China

Wen Liu, Weiping Chen, Chi Peng, Laosheng Wu and Yuguo Qian

ABSTRACT

Rainwater is an underutilized water resource that has become more important in recent years; due to severe water logging and water shortage in cities. The evaluation of rainwater harvesting potential is of fundamental importance in planning rainwater harvesting systems and management policies. In this study, we used minute-interval rainfall data and the water mass balance method coupling urban hydrological processes to assess the annual rainwater availability potential (RAP) of different underlying surfaces in the urban areas of Beijing (inside the 5th Ring Road). The estimated total RAP was 154.49 million m^3 in 2013. About 53% of rainwater could be effectively harvested for use, among which the rooftops had the highest harvesting ratio of 70%, and contributed about half of the total RAP. Indirect use of rainwater can be achieved through infiltration facilities, of which concave green land construction and porous brick pavement can increase the amount of rainfall that infiltrates into the soil by 18.89% and 55.69%, respectively. Rainwater harvesting and utilization could serve as a significant water source for the urban areas in Beijing.

Key words | green land, infiltration facilities, rainwater availability potential (RAP), rainwater harvesting, rooftop

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INTRODUCTION

Urban water scarcity is becoming worse due to population growth and economic development, degradation of the surrounding water environment, changes of the natural hydrological cycle due to land use and land cover change in urban areas, and global climate change (Konrad & Booth 2005; Aladenola & Adeboye 2010; Huong & Pathirana 2013). Increasing water availability is one of the important challenges for sustainability of urban areas, especially in many highly populated regions of the world (Kaldellis & Kondili 2007). Coupling flood control and urban stormwater runoff management with an alternative water supply, rainwater harvesting systems have grown in popularity and become an increasingly important part of urban water systems in Australia, Germany, China, and the USA (Herrmann & Hasse 1997; Coombes *et al.* 2000; Zhang *et al.* 2009; Mendez *et al.* 2011).

Rainwater can be harvested through storage devices or indirectly through groundwater recharge by means of concave green spaces, pervious brick pavements, and so on. The harvested rainwater is then used for potable and non-potable purposes as a supplementary supply in urban areas to save potable water consumption (Mendez *et al.* 2011). Due to the difficulties and expenses associated with monitoring rainwater harvesting systems, models are often utilized to determine the feasibility of rainwater harvesting at a given location, design the optimal storage tank volume, evaluate the performance of a rainwater harvesting system, and assess the benefits associated with a rainwater harvesting system (Kim & Yoo 2009; Su *et al.* 2009; Basinger *et al.* 2010; Jones & Hunt 2010; Zhang *et al.* 2012).

Rainwater harvesting potential in an urban area is dependent on the land use pattern and climatic conditions as well as soil and plant characteristics (Boers 1994; Li

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et al. 2004). In most research, the rainwater runoff volume was commonly calculated based on the runoff coefficient method or the soil conservation service (SCS)–curve number (CN) method. However, the classical methods encounter difficulties in correctly simulating the response of urban catchments to moderate rainfall events (Rodriguez *et al.* 2000), as the runoff coefficients vary considerably for different landscapes and rainfall events (Merz & Blöschl 2009). Estimation of infiltration of pervious areas can be seriously distorted while using the average rainfall without consideration of rainfall duration and intensity characteristics. It is, therefore, inadequate to use the runoff coefficient method to estimate the rainwater harvesting potential (Kahinda *et al.* 2008). In the SCS curve method, the values of CN are significantly sensitive to the runoff calculation precision (Boughton 1989). Therefore, it is necessary to develop more accurate methods to assess the potential for rainwater availability in urban areas.

In this study, we developed a water mass balance approach coupling urban hydrological cycle processes, and used minute-interval rainfall data to calculate the potential volume of rainwater availability of rooftops, hard ground surfaces, and green land under different rainwater harvesting practices. A case study of urban areas inside the 5th Ring Road of Beijing was conducted. The calculated rainwater availability potential (RAP) represents the maximum available rainwater harvesting volume, whereas the practical available volume may be much less, due to the limitations of harvesting efficiency and engineering feasibility. The method and results can provide scientific support for city managers to design reasonable harvesting measures and thus to improve sustainable water management in cities.

MATERIALS AND METHODS

Study area

The RAP within the 5th Ring Road of urban areas ($668.02\ \text{km}^2$) in Beijing, China was assessed. This region has a typical monsoon-influenced semi-humid continental climate with annual mean temperature of 13.1 °C, and annual mean evaporation of about 980 mm. The average annual precipitation (from 1951 to 2008) is 592 mm, and 81.6% (483 mm) of the total precipitation occurs in the flood season (June to September). The percentage distribution of the average monthly precipitation is presented in Figure 1.

Beijing is listed among the world's top 10 cities suffering from lack of adequate water resources. The current available water resource per capita is only $134.7\ \text{m}^3$ per year (BMBS 2012), which is about 1/20 of the national average and 1/60 of the world average, indicating that Beijing belongs to an area of extreme water deficit. Groundwater overdraft, low river flows, and water quality degradation have made the water shortage problem more serious. Therefore, the Beijing Municipal Government places a strong emphasis on rainwater collection. According to the Beijing Municipal Water Conservation Office, by the end of 2012, 898 rainwater harvesting projects had been constructed in urban areas, including water-permeable brick pavements of 3.18 million m^3, concave green spaces of 2.8 million m^3, and rainwater reservoirs of 3.27 million m^3. The collected rainwater is commonly used for greenbelt irrigation, car washing and toilet flushing.

Rainfall data

The duration and intensity of rainfall events significantly influenced the rainwater availability in a given area. The minute intervals of rainfall data for different districts of Beijing are quite scarce. In this study, we selected a year of rainfall data

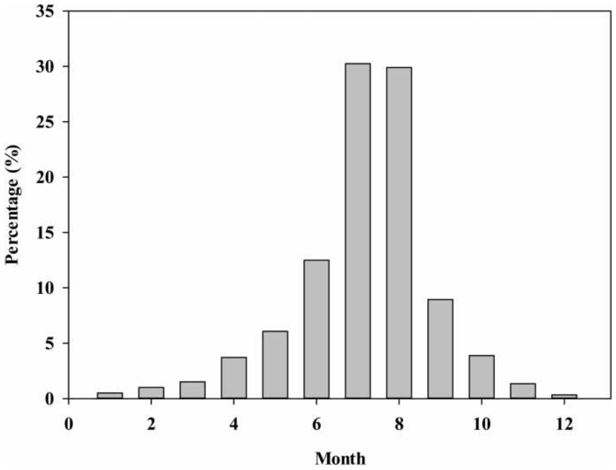

Figure 1 | The distribution percentage of average annual precipitation of Beijing from 1951 to 2008.

with 10-min intervals representing the typical rainfall events for simulation, which approached the average rainfall (592 mm) of the whole city of Beijing. According to the data from Pan *et al.* (2010), the variation of multi-annual average rainfall within the urban area of Beijing was about 3%. The spatial variability of rainfall in the urban area was ignored in this study. The rainfall data with 10-min intervals and daily temperature data in 2013 were obtained from the meteorological station of the Research Center for Eco-Environment Sciences, CAS, Haidian District, Beijing (N40°00′26″, E116°20′17″). The frequency distribution of the rainfall amount is shown in Table 1. The total rainfall amount from March to October 2013 was 473.9 mm, accounting for 98.5% of the annual precipitation of 481.2 mm.

Underlying surfaces

The types and composition of urban underlying surfaces determined the volume of rainwater runoff yield. The data on underlying surface areas were acquired through the interpretation of advanced land observing satellite images (22 October 2009) with a classification accuracy of 94.14%. The rooftops area was acquired from the map of electricity supply to buildings in Beijing. The hard ground surface area equals the interpreted impervious area minus the rooftops area. The different underlying surface areas and percentages within the 5th Ring Road of Beijing are shown in Table 2. About half of the impervious area was rooftops, while the other half was the hard ground surface area including roads, pavements, sidewalks, squares, playgrounds and parking lots. The green land area accounted for nearly one-third of the study area. Bare land, farmland, and water bodies were ignored in the rainwater potential calculation, given that their area was insignificant and runoff/overflow from them was small.

Table 1 | Statistics of rainfall events from April to October in 2013

	≤1 mm	1–5 mm	5–10 mm	10–20 mm	20–40 mm	≥40 mm
Frequency	5	25	9	5	4	3
Total rainfall (mm)	3.4	55.2	64.0	87.5	93.4	170.4
Percentage (%)	0.73	11.64	13.50	18.46	19.71	35.96

Model approaches

A mass balance approach was developed to calculate RAP based on the different urban underlying surfaces, and the whole year rainfall data of short time (10 min) intervals. Three types of urban underlying surfaces were selected: rooftops, hard ground surfaces, and green land. Runoff during the first flush of a storm event bears the highest concentration of pollutants in urban areas (Li *et al.* 2007). The initial flow is abandoned in calculating the available volume of rainwater utilization from rooftops and hard ground surfaces. The model framework is shown in Figure 2.

The volume of rainwater harvesting from rooftops is calculated by rainfall minus the initial loss and the initial split flow. The equation of rainwater availability of rooftops (R_F, m^3) can be expressed as

$$R_F = (P - L_F - B_F) \times A_F \tag{1}$$

where P is rainfall (mm), L_F is the initial loss of rooftops (mm), B_F is the initial split flow of rooftops (mm) and A_F is the rooftops area (m^2).

Similarly, the equation used for calculating the rainwater availability of hard ground surfaces (R_H, m^3) is calculated as

$$R_H = (P - L_H - B_H) \times A_H \tag{2}$$

where L_H is the initial loss of hard ground surfaces (mm), B_H is the initial split flow of hard ground surfaces (mm) and A_H is the area of hard ground surfaces (m^2).

Table 2 | The underlying surface of the urban area of Beijing (inside the 5th Ring Road)

Surface types	Rooftops	Hard ground surface	Green land	Bare land	Farmland	Water bodies	Total area
Area (km^2)	224.12	203.32	186.56	9.54	31.91	10.57	666.02
Percentage (%)	33.65	30.53	28.01	1.43	4.79	1.59	100

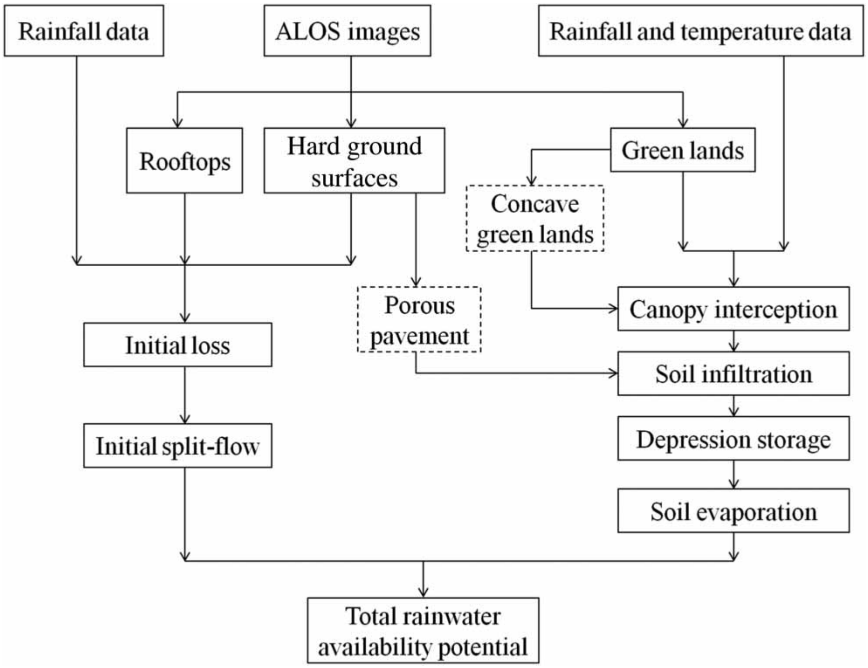

Figure 2 | Flow chart of calculating RAP and infiltration increase.

The interception and infiltration processes can significantly affect runoff from green land, especially during small rain events. When the rainfall exceeds the retention capacity of green land, the overflow runs out to hard ground surfaces and combines with the runoff draining into reservoirs. Thus, the equation to calculate the overflow from the green land (R_G, m^3) is

$$R_G = (P - C - F - D - E) \times A_G \tag{3}$$

where C is the interception by the vegetation canopy (mm), F is the infiltration into soil (mm), D is the depression storage of green land (mm), E is the evaporation of soil (mm) and A_G is the area of green land (m^2). The equation and parameters used for calculation of these terms are summarized in Table 3.

The model continuously simulates RAP of the rooftops, hard ground surfaces, and green land of all rain events in a year. The RAP of the study area is the sum of the available volume of rainwater utilization of these three types of surface.

To increase stormwater runoff mitigation potential of rainwater harvesting systems, infiltration facilities such as concave green land and porous brick pavements can be added to the system.

Table 3 | Equations used for calculation of the overflow from green land[a]

Variables	Equations
Interception	$C = S_L \times LAI$
Infiltration	$F = K_s t + S_f \Delta\theta \ln(1 + F/S_f \Delta\theta)$
Depression	$D = Sd_{max}(1 - \exp(-PC/Sd_{max}))$
Evaporation	$E = ET(1 - W_r/W_{max})$ $ET = 0.0023 \times (RA_{max}/\lambda)(T_{max} - T_{min})^{0.5}(T_{av} + 17.8)$

[a] Where S_L denotes specific leaf storage (mm), LAI is canopy leaf area index, K_s is the saturated hydraulic conductivity (mm/min), t is the time intervals of rainfall (min), S_f is suction at wetting front (mm), $\Delta\theta$ is the soil water deficit (%), which is the difference between saturated water content and the initial water content, F is cumulative depth of infiltration (mm), Sd_{max} is depression storage capacity of the green land (mm), PC is the accumulated residual rainfall (mm), which represents rainfall minus interception and infiltration, ET is the potential evaporation (mm), W_r is unsaturated water storage (mm), W_{max} is maximum allowable water storage (mm), RA_{max} is the extraterrestrial radiation of the surface related to latitude (MJ/m^2), λ is the latent heat of vapor (MJ/kg) which is usually 2.45 MJ/kg, T_{max} is the maximum daily temperature (°C), T_{min} is the minimum daily temperature (°C), T_{av} is the average daily temperature (°C).

The overflow from concave green land (R_c, m^3) is calculated by

$$R_c = \begin{cases} \left(P_c + q - f_c - \frac{1}{2}h_c\right)A_G & P_c + q - f_c > \frac{1}{2}h_c \\ 0 & P_c + q - f_c \le \frac{1}{2}h_c \end{cases} \tag{4}$$

where P_c is the net rainfall after canopy interception, q is the storage level on the concave green land of the previous time interval (mm), f_c is the infiltration of the concave green land (mm), and h_c is the depth of concave green land (mm).

The runoff from the porous brick pavement (R_p, m^3) is calculated by

$$R_p = \begin{cases} (P - \eta\Delta t + F_p - H_p)\beta A_p & P - \eta\Delta t + F_p > H_p \\ 0 & P - \eta\Delta t + F_p \le H_p \end{cases} \tag{5}$$

where η is the infiltration rate of subgrade soil (mm/min), F_p is the accumulated water volume contained in subgrade soil (mm), H_p is the maximum capacity of the porous brick pavement (mm), β is the proportion of hard ground surface paved with the porous brick pavement and A_p is the area of hard ground surface.

Parameters for the calculations

The parameters used for calculating RAP used the values found in literature (Table 4). Since Beijing is situated on a plain, the surface terrain is assumed to be flat when selecting parameter values.

RESULTS AND DISCUSSION

Total RAP

The RAP of each surface was calculated, using the model with defined parameters, rainfall data, temperature data, and interpreted underlying surface. The simulated results are summarized in Table 5.

Table 4 | The parameter values and their sources for model calculations

Parameter	Notation	Value	Unit	Source
Saturated hydraulic conductivity	K_s	0.144	mm/min	Xie *et al.* (1998)
Soil water deficit	$\Delta\theta$	14.348	%	Xie *et al.* (1998)
Wetting front suction	S_f	69.696	mm	Fu *et al.* (2002)
Maximum allowable water storage	W_{max}	121.2	mm	Ren *et al.* (2000)
Leaf area index	LAI	3.85	–	Su & Xie (2003)
Special leaf storage	S_L	0.2	mm	Wang *et al.* (2008)
Initial loss of rooftops	L_F	2	mm	Lange *et al.* (2011)
Initial loss of hard ground surfaces	B_F	3	mm	Xu (1998)
Depression storage of green land	Sd_{max}	3.5	mm	Chen & Adams (2007)
Initial split flow of rooftops	L_H	2	mm	Che *et al.* (2007)
Initial split flow of hard ground surfaces	B_H	5	mm	Che *et al.* (2007)
Infiltration rate of subgrade soil	H	0.3	mm/min	Wang (2007)
Maximum capacity of porous brick pavement	H_p	32.86	mm	Wang (2007)

Table 5 | Water mass balance for different surface types (million m^3)[a]

			Ratio of rainfall losses to rainfall (%)					
Composition	**Rainwater availability potential**	**Rainwater harvest ratio (%)**	***L***	***B***	***C***	***F***	***D***	***E***
Rooftops	74.55	70.20	13.08	16.72	–	–	–	–
Hard ground surfaces	52.26	54.25	16.46	29.29	–	–	–	–
Green land	27.67	31.30	–	–	3.74	51.39	3.19	10.38
Total	154.49	53.09	10.23	15.80	1.14	15.61	0.97	3.16

[a] *L* is the initial loss, *B* is the initial split flow, *C* is the interception by vegetation canopy, *F* is the infiltration into soil, *D* is the depression storage of green land, *E* is the evaporation of soil.

The total RAP of the study area in 2013 was about 154.49 million m^3. About 53% of rainwater could be effectively harvested for use. Rooftop surfaces had the largest rainwater harvest ratio, with 70.20% of rainfall from the rooftops being available to use, that is, the rooftop surface accounting for one-third of the underlying surface contributed 48.26% of the total RAP.

With a greater initial loss and a much greater initial split flow than those of the rooftops, the rainwater harvest ratio of the hard ground surfaces dropped to 54.25%. With a similar area to the rooftops, the hard ground surfaces had RAP of 52.26 million m^3, 22.29 million m^3 less than that from the rooftops, and it contributed 33.83% of the total RAP.

The RAP of green land was much lower than that of rooftops and hard ground surfaces. In green land, most of the rainfall infiltrated into the soil (accounting for 51.39%), and only 31.30% was available to use. The remainder was lost through interception, depression storage, and evaporation. Overall, it provided 27.67 million m^3 of RAP, contributing 17.91% of the total RAP.

In reality, the initial loss of rooftops and hard ground surfaces, and the depression storage of green land may be slightly decreased when considering the slopes of these areas. However, the water mass balance results in Table 5 indicate that the initial loss and depression storage account for about 15% and 3% of rainwater availability potential, respectively. Therefore, it implies that the impact of a small change in parameter values on rainwater availability potential is minuscule based on linear correlation.

The model was simulated by classical formulae of water mass balance and hydrological processes, thus the model accuracy could be trusted. Although it is hard to validate the model performance directly in a large-scale urban area, the runoff ratios calculated by the simulation outcomes are close to other those of other research in China. For example, based on the long-term (58 years) rainfall data and large-scale topographic map data, the average runoff coefficient of the urban area of Nanjing was calculated as 0.66 (Zhang *et al.* 2012), and the resultant runoff ratio of rooftops in Beijing was 0.62 (Zhang *et al.* 2009). The results indirectly validate the conclusion that the model predictions are in a reasonable range.

Based on the population density data from the China National Bureau of Statistics and water consumption data from the Standard of Water Quantity for Cities' Residential Use (Ministry of Construction of China, 2006), the total RAP is equivalent to 64.33% of annual domestic water consumption, and rooftop RAP alone can provide 39.84% of annual water consumption for toilet flushing for the residents within the study area (187.13 million m^3). Therefore, rainwater harvesting and utilization in the urban area of Beijing has great potential to substitute for potable water consumption.

Increasing stormwater runoff mitigation potential through infiltration facilities

Rainwater harvesting systems for hard ground surfaces and green land are often confined by limited urban spaces, costs, and water quality (Zuo *et al.* 2009). Indirect use of rainwater from these areas can be achieved through infiltration facilities such as concave green land construction and porous brick pavements. These facilities can increase the infiltration capacity, and further expand water storage in the underlying soil or recharge groundwater, and alleviate stormwater runoff and street water logging.

Significant runoff reduction and infiltration increase were observed after the conversion of green land and hard ground surfaces (Table 6). Under the rain conditions of 2013, concave green land with a depth of 5 cm decreased the ratio of runoff to 12.41%, and increased the amount of rainfall that infiltrated into the soil to 18.89%. Of the infiltrated rainfall, 70.28% was either subsequently used by plants or recharged the groundwater. Moreover, the overflow from cost-saving storage tanks of rooftops can be drained into concave green spaces to maximize the infiltration of concave green land. The hard ground surfaces paved with porous bricks decreased the ratio of runoff to 40.80%, and increased the infiltration ratio to 55.69%. Therefore, the infiltration facilities can effectively increase the stormwater runoff mitigation potential and groundwater recharge of rainwater harvesting systems. Other benefits

Table 6 | The ratios of stormwater runoff and of infiltration to rainfall for concave green land and for porous brick pavements

Surface types	Ratio of runoff (%)	Ratio of infiltration (%)
Concave green land	12.41	70.28
Porous brick pavement	40.80	55.69

such as first flush diversion and water quality improvement can also be expected from stormwater runoff reduction.

Effect of rainfall characteristics on RAP

Changes of rainfall characteristics may significantly affect the RAP for a given study area. The rainfall amount determines the volume of rainwater runoff, and the rainfall intensity affects the ratio of runoff to rainfall of green land as the soil infiltration rate is controlled by rainfall intensity.

The effect of rainfall amount on RAP was investigated by comparing the RAP in cases where the total rainfall amount in 2013 increased by 10%, 20%, 30%, 40% and 50%, respectively, while the rainfall frequency remained unchanged. The effect of rainfall increase by different amounts on the RAP for different surfaces are shown in Table 7 and Figure 3(a). As expected, the rainfall amount can substantially impact the estimated RAP. Therefore, longer records of rainfall data can reduce the variation of RAP estimation.

Table 7 | The effect of changes in rainfall amount on total RAP

	Rainfall increase percent				
	10%	**20%**	**30%**	**40%**	**50%**
Total RAP (million m^3)	176.74	199.46	222.48	245.78	269.46
Increased percent (%)	14.40	29.11	44.01	59.09	74.42

The effect of rainfall intensity on RAP was compared under a constant annual rainfall amount with different intensity distributions. All the rain events in 2013 were classified into three types according to the rainfall intensity. Light rain (when the rainfall intensity is less than 2.5 mm per hour); moderate rain (the rainfall intensity is between 2.5 and 7.6 mm per hour); and heavy rain (the rainfall intensity is more than 7.6 mm per hour), according to the *Glossary of Meteorology* (Glickman 2000). Assuming the total annual rainfall amount was constant, all the rain events were changed into the three rainfall types, respectively. These rainfall data with different intensity distributions were used as inputs for model calculations. The simulated results are shown in Figure 3(b). The total RAP was 126.82 million m^3, 145.02 million m^3, and 174.46 million m^3, and the RAP of green land was 0 million m^3, 18.20 million m^3, and 47.64 million m^3, respectively, under light, moderate, and heavy rain scenarios. The RAP of green land under heavy rain was more than twice that under moderate rain. Compared with the total RAP in 2013, the potential decreased by 17.91% and 6.13%, respectively, under light and moderate rain scenarios, and increased by 12.93% under the heavy rain scenario. Therefore, due to the large seasonal variation of rainfall intensity, rainfall data with small time intervals can improve the accuracy of RAP prediction and the reliability of rainwater harvesting system design.

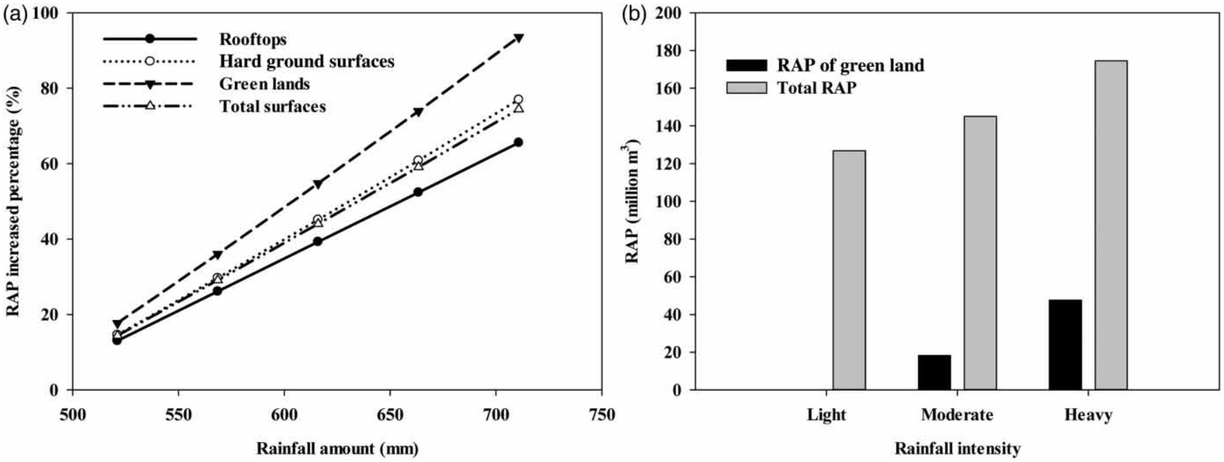

Figure 3 | (a) The RAP change under increased rainfall amounts and (b) the RAP change under different rainfall intensities.

CONCLUSIONS

The objective of this study was to assess the RAP of the Beijing urban area based on annual rain events with data at 10-min intervals, and the water mass balance approach coupling urban hydrological processes. The RAP assessment was made including aspects of potable water substitution, stormwater runoff reduction and infiltration increase. The total RAP for non-potable uses can partly substitute the potable water sources and can significantly reduce potable water demand. Rooftops have the largest rainwater harvest ratio, and thus are the best surface for rainwater harvesting by installing tanks and cisterns. Owing to the compact and limited urban space, more concave green land and porous pavements for rainwater infiltration are proposed to combine with rainwater harvesting systems to mitigate stormwater runoff and increase rainwater retention in urban areas. It was found that the model inputs, the rainfall amount and intensity, can significantly impact RAP. The rainfall data with long record periods and small time intervals can improve the accuracy of RAP prediction, and the reliability of rainwater harvesting system design.

The enormous rainwater availability potential and multiple benefits provided by rainwater harvesting are exhibited. The local government urgently needs to put in place some active measures to facilitate rainwater harvesting and utilization practices. First, the related laws and regulations, economic incentive policies, and local engineering technical norms for rainwater harvesting need to be quickly promulgated to guide the rainwater harvesting practices. Second, the government should encourage enterprises to participate in technical research and device production/construction for rainwater harvesting. Furthermore, the public awareness of rainwater harvesting should be popularized through scientific propaganda and training courses to encourage more citizens to harvest and use rainwater.

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