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5.40 Water Resources Vulnerability in the Context of Rapid Urbanization of Dhaka City (a South Asian Megacity)

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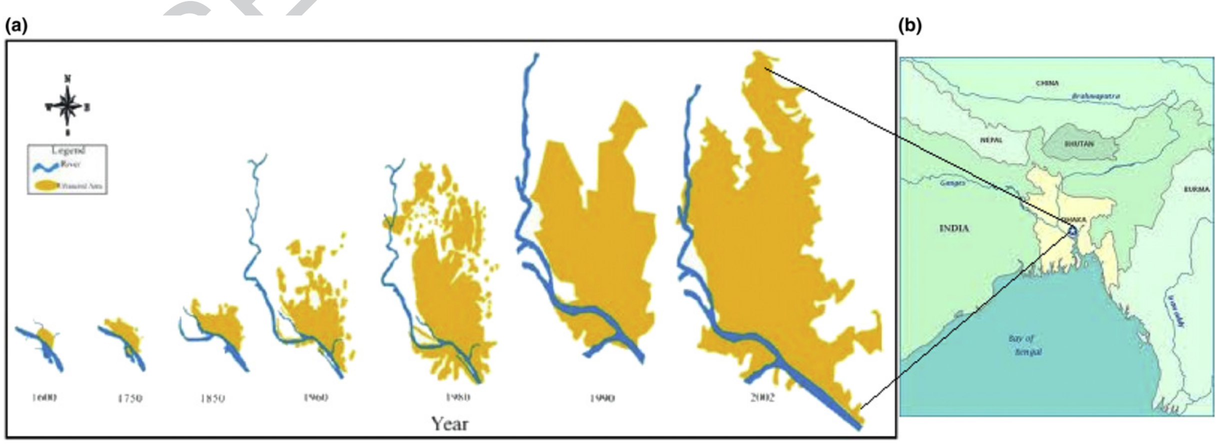
5.40.1 Introduction

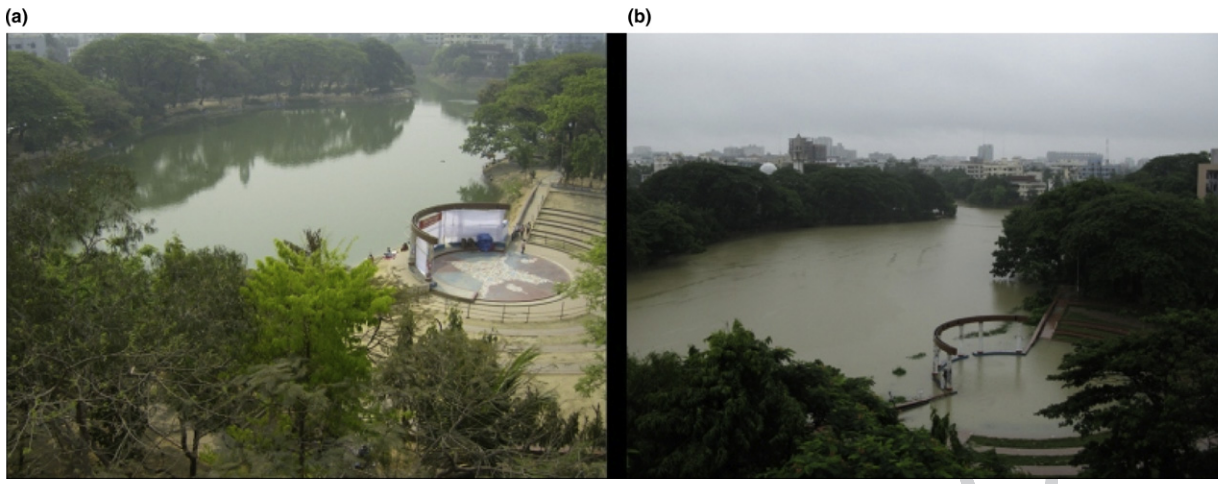
p0010 On 28 July 28 2009, a storm system spanning an area of about 3000 km^2 over the central region of Bangladesh resulted in a very heavy downpour. In just 6 h, Dhaka city – the capital of Bangladesh (Figure 1(a)), received about 448 mm of rain. In a city where urban planning, drainage, and natural wetland storage have been compromized by rapid urbanization, such a massive downpour resulted in catastrophic inundation of the city in a matter of hours (The Daily Mail 2009; Figure 2). Precipitation records maintained by the Bangladesh Meteorological Department (BMD) and the Bangladesh Water Development Board (BWDB) indicated that a 53-year record had been broken. The previous record was 326 mm on 13 July 13 1956 (SPARRSO 2010). Hereafter, the term rainfall is used as shorthand for precipitation.

p0015 Although the 28 July 2009 event occurred because of a combination of a monsoonal front and a depression in the Bay of Bengal (SPARRSO 2010), recent records of comparable-magnitude events appeared to have occurred exclusively near large cities (341 mm of rain in 24 h on 14 September 2004 in Dhaka and 425 mm of rain in 24 h on 11 June 11 2007 in the second largest city, Chittagong). Given that Bangladesh has a fairly comprehensive monitoring network of rainfall across the largely rural and agricultural country (254 daily recording stations since 1950; Figure 3), the possibility of land use change (such as urbanization) having played a role in precipitation, runoff generation, and groundwater recharge modification deserves a careful look. For a historical trend of land use change since the beginning of Dhaka City in AD 1600, the reader is referred to the left panel of Figure 1(b). A question that has never been asked by water policy planners and scientists alike is – *Does the urbanization of Dhaka city over the past 20 years in a largely rural–agricultural surrounding have any detectable effect on local and regional precipitation and runoff patterns?*

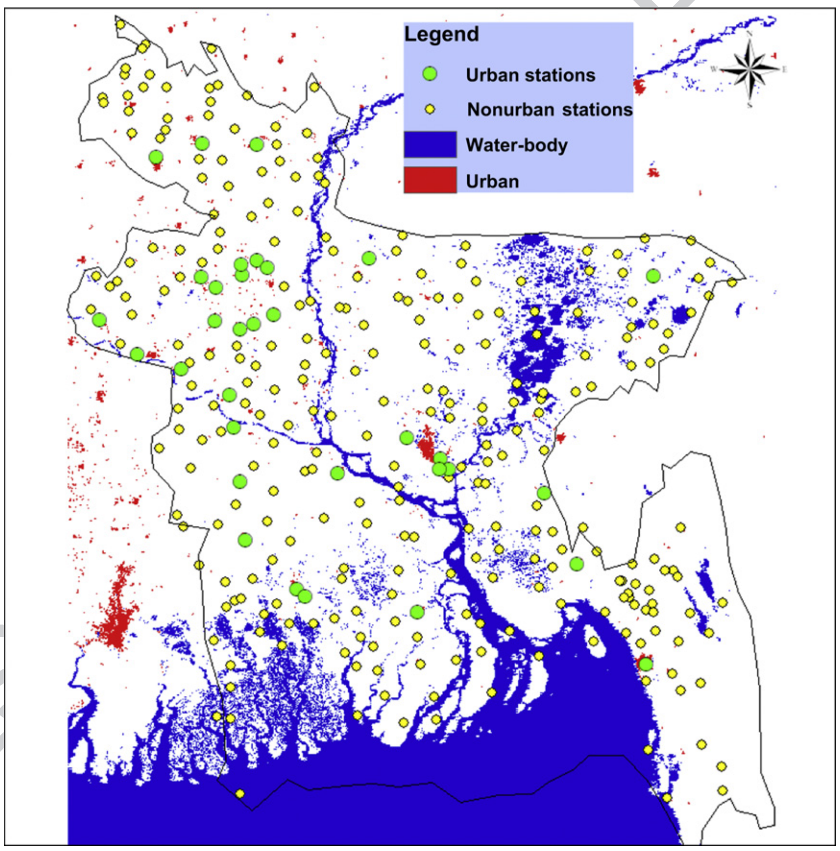
The above question is timely for a number of reasons. Dhaka is the fastest growing megacity in the world with an urban population now close to 14 million (World Bank 2010). p0020



f0010 **Figure 1** (a) Dhaka city growth since AD 1600 and (b) location of Dhaka in Bangladesh.



f0015 **Figure 2** The flooding impact of the 28 July 2009 storm in Dhaka city. (a) Dhanmondi Lake located near a Dhaka suburb during March 2009 (dry season) and (b) 12 h after the storm on 28 July 2009 ended. Source: Sébastien Rist and Aude leroux-Lévesque at http://bideshifilms.com.



f0020 AU15 **Figure 3** Location of the 254 daily recording rainfall stations from the BMD and BWDB network. Colors green and yellow classify stations as 'urban' and 'nonurban,' respectively, according to MODIS land use classification data.

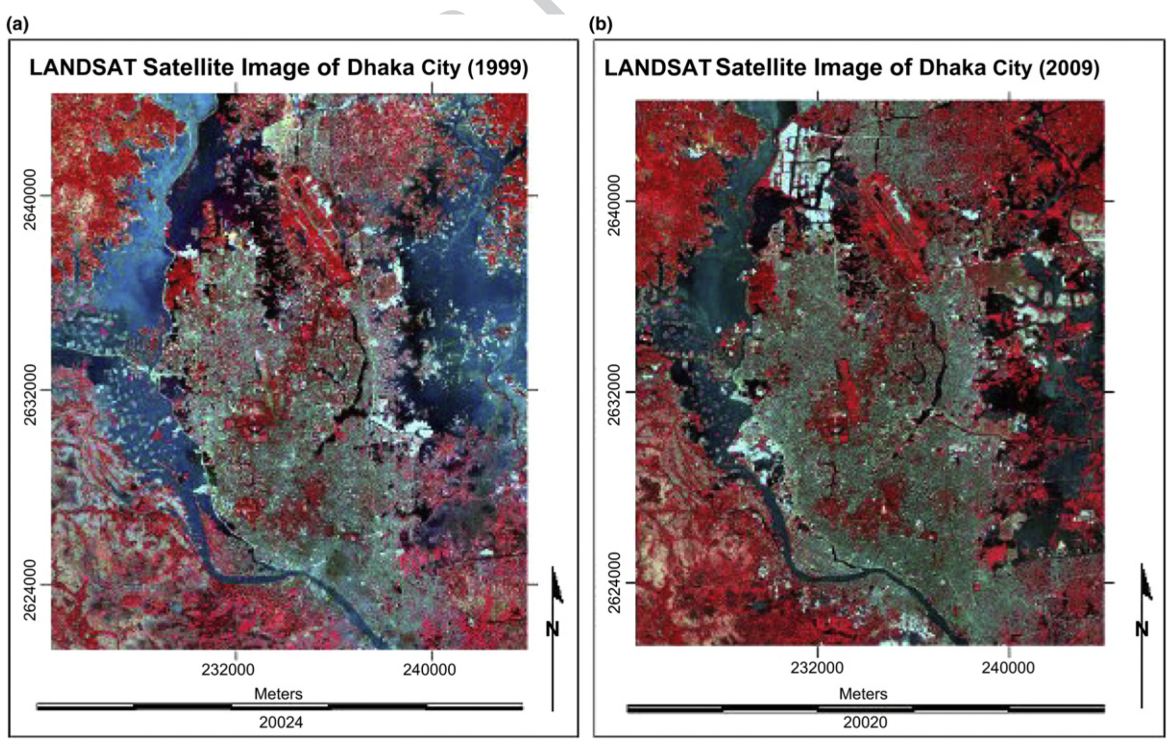
By 2015, the United Nations (UN) predicts that Dhaka's population will exceed that of Mexico City, Beijing, or Shanghai (Table 1; United Nations 2001). Such a growth rate adds tremendous pressures on the city's renewable but finite water resources for domestic consumption. With ground water table decreasing at the rate of 2–3 m year^{-1} (Rahman and Hossain 2008) and the recharge zone of the deep aquifers of Dhaka (that supply 80% of the city's safe drinking water) becoming progressively encroached, sustainable water resources development is already a challenging task. The encroachment of pervious area or natural wetlands by unplanned urbanization can be appreciated in Figure 4, in which two LANDSAT images t0010 **Table 1** Population and growth rate of some of Asian megacities (UN, 2001)

Megacity	*Population (millions)*	*Annual growth rate (2005–2015) (%)*
Dhaka, Bangladesh	12.6	3.2
Shanghai, China	12.7	1.1
Calcutta, India	14.3	2.0
Jakarta, Indonesia	13.2	2.7
Delhi, India	15.3	2.2
Mumbai, India	18.3	2.2

taken a decade apart show drastic changes in the spatial extent of natural water bodies. The large-scale arsenic contamination of shallow but the more abundant ground water available in the rest of the country (Hossain and Sivakumar 2006) makes the dependence on a single source of water (such as the deep aquifers of Dhaka) a risky option for the future. Other sources, such as surface water resources, therefore need to be explored. It is for this reason that the Bangladesh Government has recently started to explore the viability of withdrawing the polluted river waters around Dhaka city as a mitigating source for the dwindling supply of ground water (Rahman and Hossain 2008).

p0025 If surface water is to be assessed of its future potential, the impact of changing trends on rainfall and runoff generation (owing to rainfall partitioning and land use patterns) needs to be understood. Climate projections according to the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) indicate that the humid regions of South Asia would be significantly altered in terms of rainfall patterns later in the century (Schneider et al. 2007). If such climate projection is to be believed, then the long-term planning for adaptation must consider the local-to-regional feedbacks between the atmosphere and urbanizing land surface. Such a more 'local' approach can be considered more robust as part of the recently coined 'bottom-up vulnerability' assessment approach of a resource in a changing climate (Pielke et al. 2011). In line with previous arguments articulated by Pielke et al. (2009), this vulnerability concept requires the determination of the climatic threats to a resource (such as water), as well as from other socioeconomic and environmental issues. The relative risk from natural and man-made climate variability and longer-term change is then compared with other risks for adopting the optimal mitigation/adaptation strategy. Hossain et al. (2011) argues that the advantage of this bottom-up vulnerability strategy, which must consider the local-to-regional climate feedbacks, is that even if the forecast of water availability because of model projections or other threats were wrong years later, the optimal adaptation strategy identified from multiple threats should have allowed for this error during planning.

Although Bangladesh has an intricate network of rivers, surface water withdrawal from adjacent rivers is not an immediately viable option for Dhaka city because of high levels of industrial pollution from unregulated waste disposal (Kamal et al. 1999). On the other hand, the rainfall and the generated urban runoff (for artificial recharge) around Dhaka city may be a more cost-effective option for water harvesting given the successful experience of more advanced cities faced with perennial water scarcity. For example, the Seletar–Bedok stormwater harvesting scheme in Singapore is an urban runoff capturing system, in which almost one-quarter of the p0030



f0025 **Figure 4** Rapid urbanization and encroachment of pervious area and natural wetlands around Dhaka City as evidenced from LANDSAT images taken during 1999 (a) and 2009 (b).

catchment is in urban area with high rise buildings and impervious surfaces (PUB 2011). The urban runoff generated during storms is directed to a nearby reservoir where it is treated for redistribution through Singapore's drinking water network. If the sustainability of such an urban runoff/rainfall harvesting system is to be explored, rainfall and runoff patterns around Dhaka city needs to be identified in the context of rapid land use change.

p0035 There is now considerable evidence that suggests that urbanization can modify rainfall patterns due to a combination of factors (see Mahmood et al. (2009); Shepherd et al. (2010a) for comprehensive reviews), such as (1) increase in cloud condensation nuclei (CCN) concentrations (Ashworth 1929; Rosenfield et al. 2008), (2) changes in surface roughness and low-level convergence (Avissar and Pielke 1989; Shepherd et al. 2010b), or (3) urban heating and land use changes (Bornstein and Lin 2000; Shem and Shepherd 2009). Such changes, independently or synergistically, alter fundamental processes associated with precipitation formation or enhancement (i.e., sensible and latent heat fluxes, convergent flow, cloud water development, and direct thermal circulation patterns). AU3

p0040 For example, observational evidence spanning a decade of rainfall measurements indicates that rapid urbanization in the Pearl River Delta of China has reduced precipitation (Kaufmann et al. 2007). However, this study only included urban land cover and no aerosol forcing, which has been shown to suppress precipitation (Rosenfield et al. 2008). A follow-up study reported that the reduction in precipitation was more during the winter season (Seto and Kaufmann 2009). Kishtawal et al. (2009), in a study over the Indian region, found that the frequency of heavy precipitation had actually increased near areas of urbanization. A very recent series of studies by Mitra et al. (2011) has examined changes in premonsoon rainfall in a region near Dhaka city, specifically Kolkata in India. They found evidence that rainfall in the urban observation stations of Kolkata had statistically significant increases over the past 50 or so years, whereas rural stations, the east Gangetic region, and the country itself exhibited no such trends. Lei et al. (2008) found evidence that urbanization in Mumbai, India, contributed to a heavy rainfall event on 26 July 26 2005. Recent papers by Shem and Shepherd (2009) and Niyogi et al. (2011) have further confirmed that urban land cover can enhance existing convective precipitation systems. Recent studies (such as Molders and Olson 2004; Shem and Shepherd 2009; Bentley et al. 2009; Shepherd et al. 2010a,b; Niyogi et al. 2011) provide a comprehensive review of the literature on the role of urbanization on the rainfall process and establish that such observations are prevalent in many different geographic, climatic, and seasonal regimes. These studies report the considerable debate on the underlying causes and whether urbanization categorically increases or decreases the intensity and frequency of rainfall. However, most studies agree that under the right circumstances, the urbanization signature on rainfall is detectable. AU4

p0045 Regardless of urbanization having a direct impact on the ambient meteorological process of rainfall generation, the study of rainfall patterns in an urban setting is important for sustainable water resources planning because of the urban runoff generation potential of heavy storms. For example, Ntelekos et al. (2007) reported a close relationship between major flash flooding and heavy thunderstorms for Baltimore city (USA) where high urban runoff generation potential was found to be the key factor in overwhelming storm drainage systems. In the study of the recent disastrous flood of Atlanta (in Georgia, USA) in September 2009, Shepherd et al. (2011) found some evidence that urban land cover interactions could have influenced the distribution of the heaviest rainfall and consequential high urban flooding around the city. The frequent urban flooding that is expected to become more frequent and flashier with increasing urbanization is rarely viewed as a 'resource' to mitigate water supply shortage. It seems that only the very advanced cities faced with a historical shortage of water have infrastructure in place to treat urban runoff as a 'resource'. For example, in Singapore, there are several urban runoff capturing reservoirs such as the Seletar–Bedok system (alluded earlier) under construction that aim to convert one-third of Singapore's total area as catchment for urban runoff and reuse, thereby reducing its future dependence on neighboring Malaysia for importing water (PUB 2011).

This study is motivated by the need to assess the water resources vulnerability of the Asian megacity of Dhaka in Bangladesh faced with challenges from climate and socioeconomic pressures. Toward this assessment, the study investigates the rainfall patterns and surface runoff generation potential around Dhaka city in the context of rapid urbanization, which can be viewed as a potential forcing for climate (modification of rainfall process in the atmosphere) and hydrology (modification of runoff transformation on the surface). There are three parts to the study: (1) long-term statistical analysis of rainfall in urban and nonurban regions of Bangladesh to understand the baseline behavior of the greater region, (2) dissection of the weather patterns around Dhaka City during the 28 July 2009 storm event, and (3) rainfall runoff simulations to estimate the potential for harvesting urban runoff from rainfall. p0050

5.40.2 Twenty-Year Analysis of Rainfall Patterns in Urban and Nonurban Regions of Bangladesh s0015

Using daily rainfall records from 254 locations in Bangladesh, the first part of this study investigated the statistical difference between the historical patterns in urban and nonurban regions. The station locations pertained to the combined monitoring network of BMD and BWDB and are shown in Figure 3. Land use/land cover data was obtained from Moderate Resolution Imaging Spectroradiometer (MODIS) Land Cover Type product (Friedl et al., 2002). In this case, the 14-class University of Maryland Classification was used. Accordingly, a binary 'urban' and 'nonurban' classification of the Bangladesh land surface was made. The rainfall monitoring stations located inside an urban area were selected as 'urban' stations, whereas the rest of the stations were classified as 'nonurban'. A total of 24 stations were classified as 'urban' and 230 stations as 'nonurban' using the binary MODIS-based land use classification. Rainfall record for each station spanned 20 years from the mid-1980s to the mid-2000s. p0055 p0060 Rainfall histograms were created for four categories: urban monsoon, nonurban monsoon, urban all season, and nonurban all season. From these histograms, the percentiles for the mean, 90% (P90), 95% (P95), and 99% (P99) non-exceedance probability were derived for unconditional and conditional cases (Tables 2(a) and 2(b)). The conditional case (considering only the nonzero rainfall data) is expected to remove the effect of long dry spells during winter months that can mask an underlying trend in the extreme percentiles. Because most of the heavy thunderstorms or 'norwesters' occur during the spring season before the onset of the monsoon season (known locally as 'kalbaisakhi') (IMD Report 1941; Weston 1972), conditional analysis was also carried out for the April–June period (Table 2(c)). This analysis is consistent with the rationale of Mitra et al. (2011), who conducted a similar analysis for Kolkata (in India).

p0065 The percentile values reported in Tables 2(a)–(c) indicate that, in all cases (monsoon, all season, and spring), nonurban rainfall is statistically larger than urban rainfall. In order to explore a possible impact on occurrence of heavy rain, analysis was also carried out to observe the effect on frequency of rainfall. The analysis was broken down for heavy events that registered more than 20 mm day^{-1} of rain. Figure 5 confirms that on average, in Bangladesh, nonurban regions experience more days of rainfall than urban regions. Overall, observational data indicates a general suppression of all types of rainfall events in terms of both intensity and frequency in urban regions of Bangladesh.

p0070 Although the results appear to agree with a similar study carried out by Kaufmann et al. (2007), where they report for the Pearl River Delta that "This reduction may be caused by changes in surface hydrology that extend beyond the urban heat island effect and energy-related aerosol emissions," there a number of unresolved issues to keep in mind for this study. The presence of particulate matter in air of size less than 10 μm that suppress rainfall and are likely to be present in industrializing environments, was not considered by Kaufmann et al. (2007). In Bangladesh, brick kilns, located in close proximity to urban regions, operate from October–April to supply bricks for the construction season. These kilns have been found to be the major contributor of fine particulate matter in the major metropolitan areas of Bangladesh (Guttikunda 2009). On the other hand, Kishtawal et al. (2009) and Hand and Shepherd (2009), among others, found a strong relationship between urbanization and heavy rain events, where the impact was usually observed 25–100 km downwind. Hence, a more complete analysis, which is beyond the scope of this study, would require clustering rainfall stations as 'urban' based on a 25- to 100-km downwind proximity to a city rather than on land use alone.

t0015 **Table 2a** Statistical summary of rainfall histogram both for urban and nonurban regions for the unconditional case (where rainfall ≥ 0.0 mm day^{-1})

	Precipitation (mm day^{-1}) – all days (unconditional)				
	Mean	*Std. Deviation*	*P90*	*P95*	*P99*
Urban (All season)	5.67	17.30	12.75	29.50	78.84
Nonurban (All season)	7.04	20.00	17.54	36.19	91.67
Urban (Monsoon)	11.92	23.78	31.35	51.98	107.92
Nonurban(Monsoon)	14.47	27.18	37.22	60.79	115.50

Table 2b Statistical summary for rainfall percentiles of the urban and nonurban regions for the conditional case (where rainfall > 0.0 mm day^{-1}) t0020

	Precipitation (mm day^{-1}): rain days (Conditional)				
	Mean	*Std. deviation*	*P90*	*P95*	*P99*
Urban (monsoon)	21.59	28.55	48.83	71.95	133.33
Nonurban (monsoon)	25.24	31.88	55.49	81.11	154.68
Urban (All season)	20.82	28.00	46.12	68.04	130.24
Nonurban (all season)	24.61	31.06	53.65	77.88	146.05

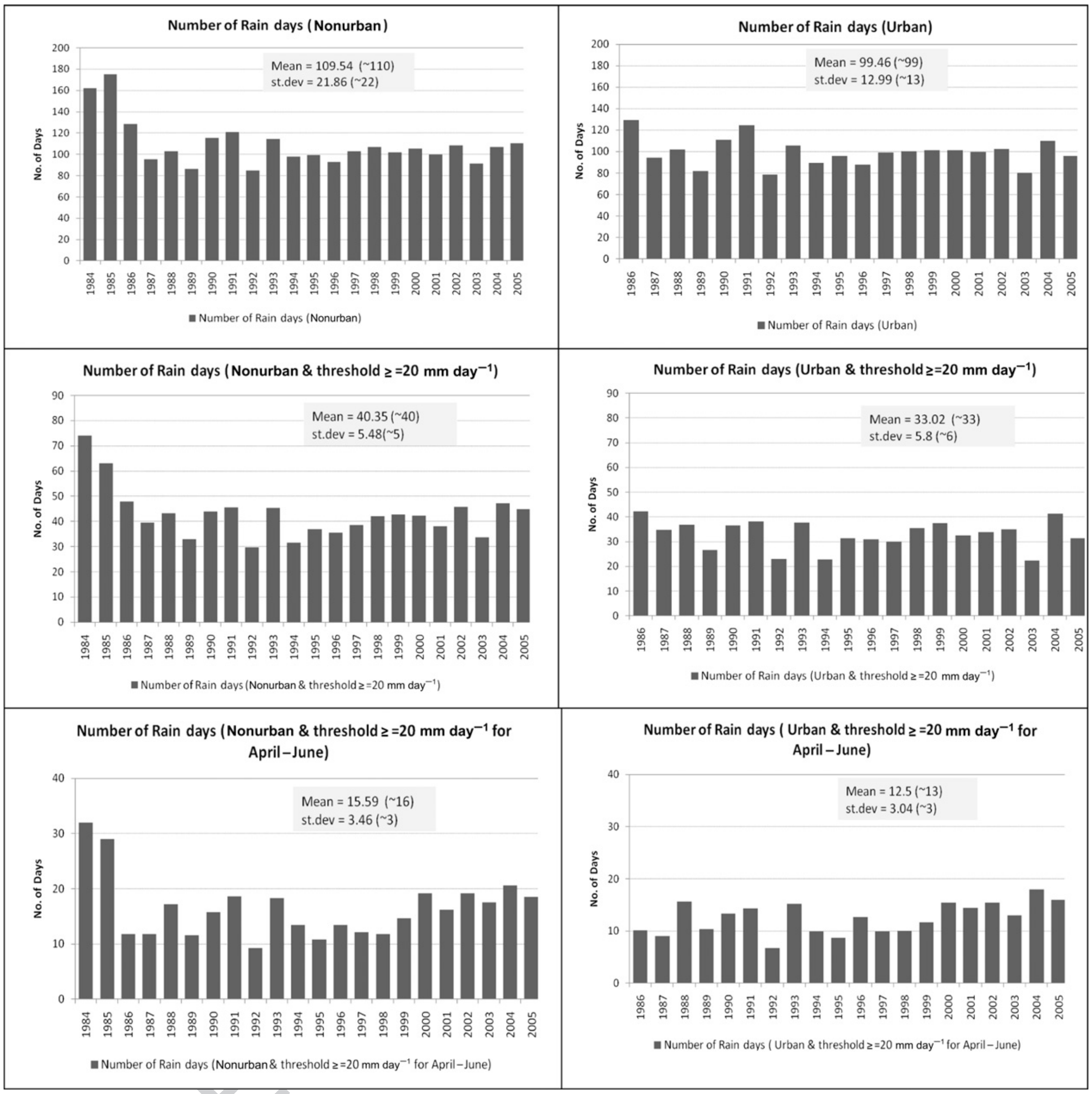
Table 2c Same as **Table 2b** but for April–June (conditional case) t0025

	Precipitation (mm day^{-1}) (April-June)				
	Mean	*Std. deviation*	*P90*	*P95*	*P99*
Urban	20.55	23.66	43.22	59.25	104.29
Nonurban	24.06	28.17	49.5	69.55	125.00

Another point to consider is the presence of irrigation, which may play a defining role on modifying precipitation patterns. Bangladesh initiated its green revolution for rice production in the late 1970s through massive expansion of groundwater and surface water irrigation schemes in order to allow three major crop growing seasons a year. A study supporting this point was carried out by Lohar and Pal (1995) to understand the effect of irrigation on premonsoonal rainfall over South West Bengal. They concluded that irrigation reduced the low-level moisture and increased soil moisture. They hypothesized that these processes decreased the intensity of sea breeze circulation and related convection. Therefore, the perennially ponded paddy fields may explain to a large extent the statistical difference between the rainfall percentiles for nonurban and urban regions. p0075

5.40.3 Analysis of the 28 July 2009 Storm Event s0020

According to the Bangladesh Space Research and Remote Sensing Organization (SPARRSO) annual report published in 2010, the 28 July 2009 storm had its genesis in the Bay of Bengal. An area of low pressure formed in the Bay of Bengal on 26 July 2009 that gradually transformed to a fully developed low on 27 July. This then intensified into a depression and subsequently moved to Dhaka City along the northeastern direction producing very heavy rainfall over Dhaka and surrounding regions (SPARRSO 2010). To closely scrutinize the makeup of the storm and understand the possible signature of urbanization, atmospheric reanalysis data was derived from the Modern Era Retrospective-Analysis for Research and Applications (MERRA). The surface sensible heat and latent heat and specific humidity were derived at the level of 850 hPa for the date of the storm. The accumulated rainfall for the same date was acquired using the Tropical Rainfall Measuring Mission (TRMM) Multisatellite Precipitation Analysis (TMPA) p0080 AU5 AU6

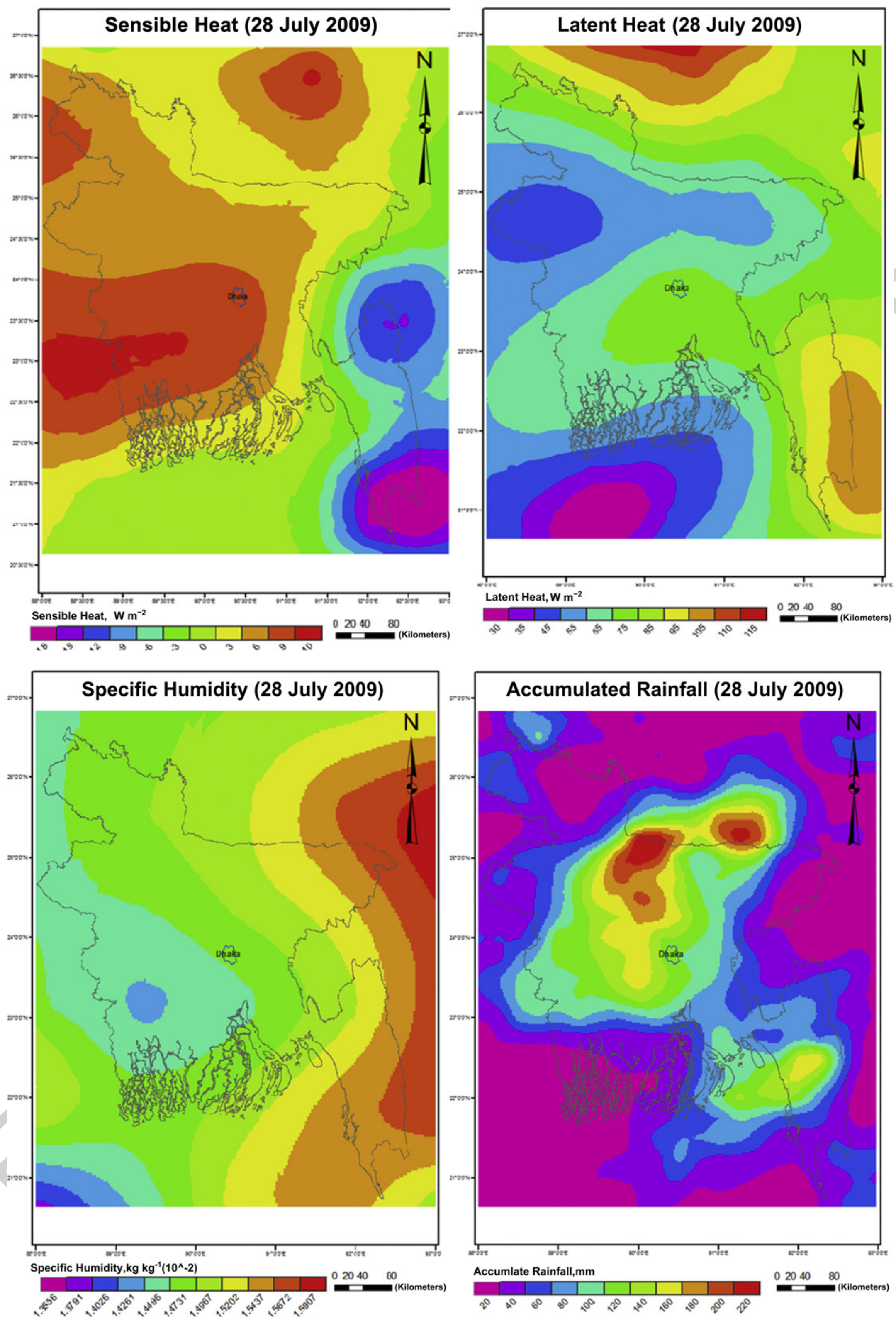


f0030 **Figure 5** Rainfall frequency analysis for urban and nonurban regions of Bangladesh. Frequency is shown here as the number of rainy days per year for each year. (a) Nonurban and (b) urban. Lowermost panel shows frequency for rain events greater than 20 mm day^{-1}.

(Huffman et al. 2009). The resolution of the data ranged between 0.25–1.25°.

p0085 Generally, a decrease in sensible heat with a corresponding increase in latent heat and specific humidity is observed from west to east (Figure 6). Although urbanization is expected to result in increased (decreased) sensible heat (latent heat), the resolution of MERRA data is very coarse to attribute any specific change to Dhaka City. The systematic increase of specific humidity along the northeastern direction is indicative of the underlying synoptic condition where monsoonal winds during the months of July–August flow over Bangladesh in the northeaster direction and collide with the mountains in Assam (India).

In order to identify the prevalent wind direction on 28 July 2009 and the historical wind rose diagram, the daily average of eastward and northward wind speed values at 850 hPa were used to determine the direction of wind (Figure 7). For the historical wind rose diagram for July, wind speed data spanning 5 years was used to create the probabilistic map of wind direction and speed using Dhaka city as the center. As expected, historical wind direction and the prevalent wind direction (on 28 July 2009) are found to be in the northeast direction. Using this direction, a group of 10 (eight) rainfall stations was identified as upwind (downwind) of Dhaka city (Table 3). The percentiles (P90, P95, and P99 and the mean) were calculated for the upwind and downwind stations using the 20-year p0090



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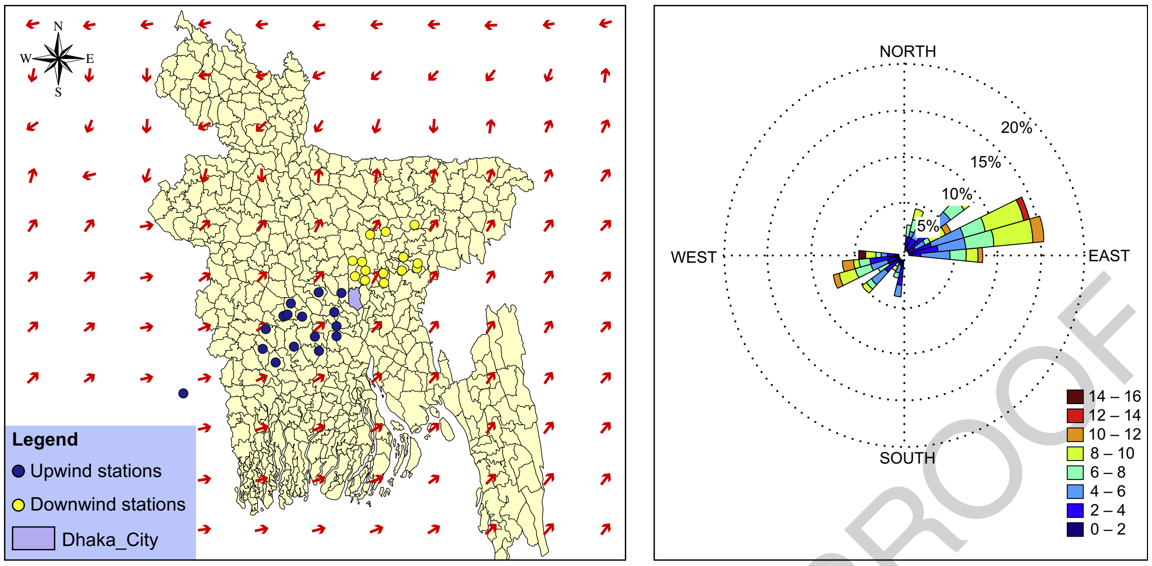
f0035 **Figure 6** Map of daily averaged sensible heat, latent heat, specific humidity, and accumulated rainfall for 28 July 2009 over Bangladesh.



f0040 **Figure 7** (a) Prevalent wind direction at 850 hPa on 28 July 2009. Blue and yellow colored rainfall stations represent upwind and downwind locations, respectively. (b) July windrose diagram for Dhaka city using 5 years of wind data.

t0030 **Table 3** Upwind and downwind stations of Dhaka city derived from MERRA wind direction

Upwind station			*Downwind station*		
Station name	*Longitude*	*Latitude*	*Station name*	*Longitude*	*Latitude*
Manikganj	90.0039	23.850	Sreepur	90.5088	24.1475
Rajbari	89.6746	23.7403	Bajitpur	90.9872	24.1940
Baliakadi	89.5934	23.6181	Kishoreganj	90.7782	24.4529
Bhagyakul	90.2128	23.5154	Shibpur	90.7568	24.0365
Bhanga	89.9579	23.4089	Bhairab Bazar	90.9678	24.0694
Fatehpur	90.0039	23.2708	Itna	91.1150	24.5184
Shibchar	90.2157	23.4229	Sarail	91.1463	24.0916
Magura	89.3919	23.4832	Nasirnagar	91.1604	24.1351
Narail	89.5029	23.1573	–	–	–
Salikha	89.3512	23.2870	–	–	–

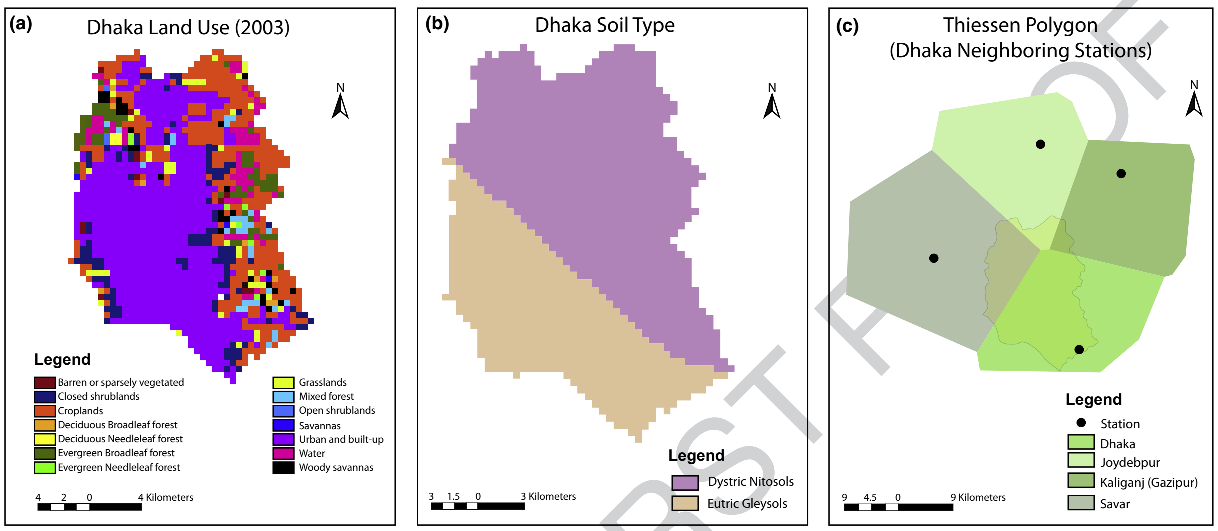
record of data (Table 4). On an average, it seems the downwind region east of Dhaka city receives about 4 mm more of rainfall a day than its upwind counterpart, which is consistent with historical and contemporary studies (Mote et al. 2007).

p0095 Although downwind rainfall is found to be higher for Dhaka city, any physical and direct attribution to urbanization for the 28 July 2009 storm cannot be made given the prevalent condition of a depression in the Bay of Bengal that lasted a few days. For such a land-falling low-pressure system, regions further along the wind direction (such as downwind region east of Dhaka) are naturally expected to experience more rainfall. Lei et al. (2008) studied the catastrophic storm of 26 July 2005 in Mumbai (India) that had similar background synoptic conditions as the 28 July 2009 storm in Dhaka. Using atmospheric modeling, they reported that urbanization potentially contributed to local heavy precipitation at local hotspots and mesoscale precipitation distribution over the Indian monsoon region. Although the urban effect by itself was not found dominant, urbanization appeared to have created conditions that sustained the convergence zone over Mumbai during the duration of the storm.

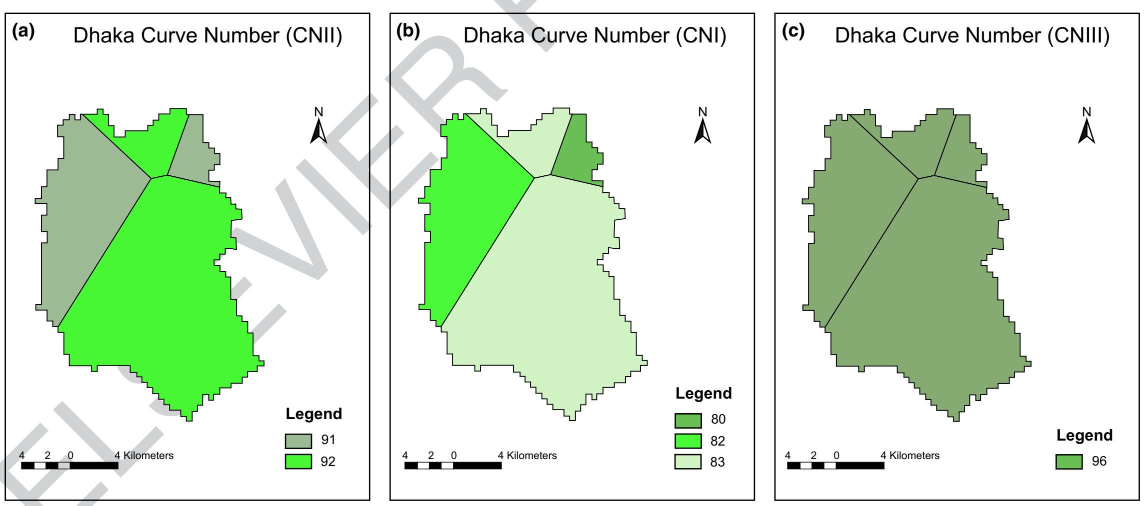
5.40.4 Assessment of Urban Runoff Generation Potential s0025

In order to understand the ballpark surface water availability from urban runoff generation, a curve number (CN) model was set up to estimate the rainfall partitioning as runoff and recharge/storage. A spatially distributed CN map was first created using high-resolution maps on land use (from LANDSAT) and soils (from Food and Agricultural Organization) at 500 m × 500 m resolution (Figures 8(a) and 8(b)). These two maps were overlaid to derive the CN for each 500 m × 500 m grid box over Dhaka city. There were a total of 1522 grid boxes. A Thiessen polygon map was generated using four rainfall stations near Dhaka city (Figure 8c). The CNs were then lumped as one value (area-weighted composite) for each of the p0100 t0035 **Table 4** Statistical summary of rainfall percentiles for stations upwind and downwind of Dhaka City in **Table 3** for conditional case (rainfall > 0.0 mm day^{-1})

	Precipitation (mm day^{-1})				
	Mean	*Std. deviation*	*P90*	*P95*	*P99*
Upwind stations	18.93	23.16	40.63	58.92	106.3
Downwind stations	23.58	27.25	51.12	72.25	127.9



f0045 **Figure 8** Dhaka City land use (a) and soil type (b), and Thiessen polygon for neighboring stations (c).



f0050 **Figure 9** Dhaka City curve number map for the three antecedent moisture conditions (AMC) – moderate-II (a), dry-I (b), and very wet-III (c). Curve numbers are lumped according to Thiessen polygon representative regions for each station in and near Dhaka City (c).

four Thiessen polygon representative areas of Dhaka city shown in Figure 9. The four rainfall stations were Kaliganj, Dhaka, Savar, and Joydebpur. The preceding 5-day rainfall total was used to determine the antecedent moisture condition (AMC) for each day as I (dry), II (moderately wet), or III (very wet) following the method outlined in Chow et al. (1988) and summarized in Table 5.

The interesting picture that is revealed from this CN-based runoff analysis is that, on an average, about 62% of rainfall usually transforms as runoff and eventually drains into the peripheral rivers of Dhaka as an 'untapped' resource (Table 6(a)). The remaining 38% of rainfall may be considered as a combination of 'recharge,' evaporative losses, and temporary storage. Measurements of groundwater table in Dhaka city p0105 t0040 **Table 5** AMC classification for curve number model based on preceding 5-day total rainfall

	Total 5-day antecedent rainfall (in.)	
AMC group	*Dormant season (Oct–April)*	*Growing season (Apr–Sep)*
I	<0.5	<1.4
II	0.5–1.1	1.4–2.1
III	>1.1	>2.1

Source: After Chow V. T., D. R. Maidment, L. W. Mays, 1988: *Applied Hydrology.* McGraw-Hill International Editions, Civil Engineering Series.

indicate that the table is declining at the rate of 2–3 m year^{-1}, indicating that the uptake is not sustainable in comparison to natural recharge rates (Rahman and Hossain 2008). On the other hand, for a heavy storm, such as on 28 July 2009, more than 95% of the rainfall transforms as surface runoff and eventually drains into rivers and water bodies (Table 6(b)). If the rainfall and the urban runoff from moderate-to-heavy storms could be harvested, it could provide Dhaka with an alternate supply of water to relieve the pressure on its dwindling and renewable water resources.

s0030 5.40.5 Discussion

p0110 What could be the strategy for future water resources planning based on the above vulnerability assessment in the context of rapid urbanization? There are two key findings that can be used to promote sustainable use of water resources for a megacity such as Dhaka. First, rainfall has a spatial gradient where the downwind region seems to receive statistically higher rainfall than the upwind region. Although such a spatial pattern cannot yet be physically attributed to rapid urbanization, the observation itself has merit for policy planners. Second, urban regions around Bangladesh in general receive less rainfall than the nonurban regions. At the current state of urbanization for Dhaka city, approximately 62% of the rainfall is available as urban runoff, which currently is untapped as a potential mitigating source.

Such a preliminary assessment of urban runoff points to the feasibility of a Seletar-Bedok-type urban runoff harvesting reservoir as in Singapore for supplementing the traditional aquifer-based water supply. At the current growth rate, water demand for Dhaka city is expected to reach 3.2 million m^3 per day (Mm^3/day), or 3200 million l day^{-1}, by 2025 (Figure 10). According to the CN-based runoff assessment shown in Table 5, the long-term daily runoff generation potential for Dhaka city is around 3.06 Mm^3 day^{-1}. Assuming a 50% urban runoff capture efficiency for a runoff harvesting reservoir, about 0.7 Mm^3 day^{-1} of this urban runoff may be used for artificial recharge to systematically raise the groundwater table. The remaining 0.8 Mm^3 day^{-1} amount could be treated for suspended solids removal and then used for nondrinking consumption. Such a conjunctive approach would not only relieve pressure on the deep aquifers, but also gradually counter the declining groundwater table and build strategic storage for use later in the century. For the heavy storms, more than 90% of the rainfall is generated as runoff. This indicates that rainwater harvesting should be promoted in the downwind regions located east of Dhaka city and transported back for urban consumption as drinking water through bottling or a network of pumping stations and pipe networks. p0115 AU7

A recent pilot-scale study implemented by the Bangladesh Institute of Water Modeling (IWM) for Dhaka Water Supply and Sewerage Authority (DWSSA) during 2011 indicated that rainfall and runoff harvesting can indeed be successful in cost-effective recharge of ground water by using injection well by gravity (IWM 2011). In fact, this pilot-scale study demonstrated that if "*60% of the total rainfall from concrete roof tops of the city area can be harvested then annually about 89,496 millions of liters rain water will be available for artificial recharge to aquifer…can* p0120

t0045 **Table 6a** Long-term 10-year water balance for Dhaka City (1986–1995)

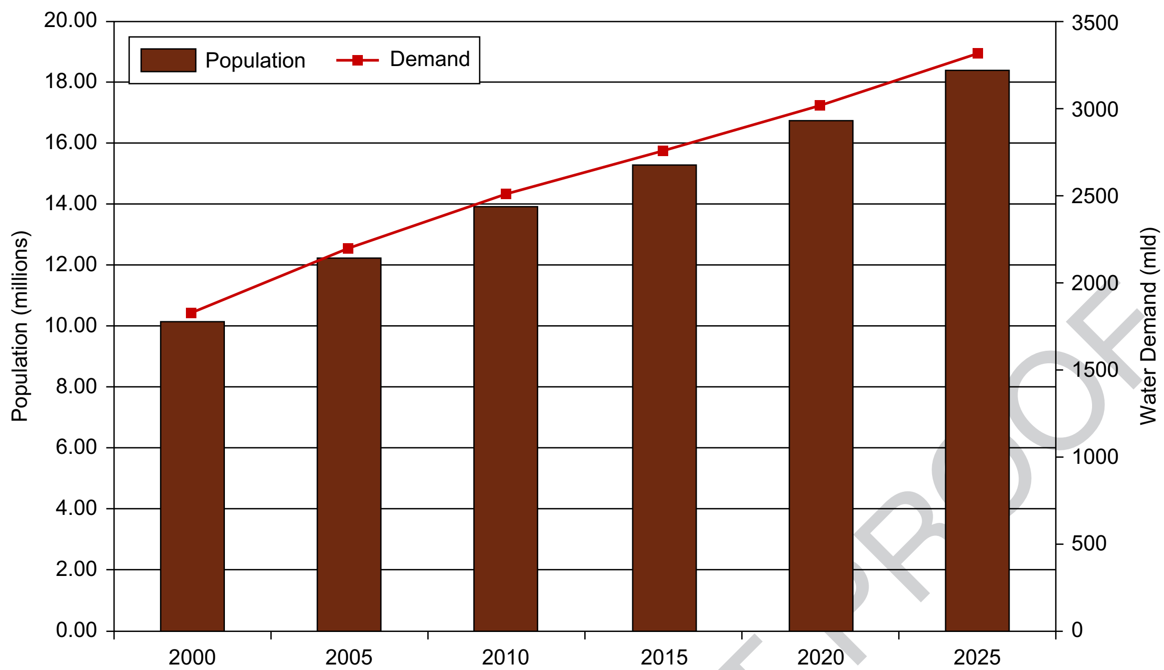
CN region based on Thiessen polygon rainfall station	*Representative area (km^2)*	*Total rainfall volume (Mm^3)*	*Total runoff volume (Mm^3)*	*Total storage volume (Mm^3)*
Kaliganj (Gazipur)–Joydebpur	16.69	548	286	262
Joydebpur	24.75	814	425	388
Savar	96.00	4487	2745	1741
Dhaka	243.06	12 184	7712	4472
Total	380.50	18 035 (100%)	11 170 (62%)	6864 (38%)

Mm^3, million cubic meter.

t0050 **Table 6b** Water balance for Dhaka city on July 28, 2009

CN region based on Thiessen polygon station	*Representative area (km^2)*	*Rainfall volume (Mm^3)*	*Runoff volume (Mm^3)*	*Storage volume (Mm^3)*
Kaliganj (Gazipur)–Joydebpur	16.69	4.61	4.41	0.21
Joydebpur	24.75	6.84	6.54	0.30
Savar	96.00	10.08	8.96	1.12
Dhaka	243.06	108.89	105.86	3.03
Total	380.50	130.43 (100%)	125.77 (96%)	4.66 (4%)

Mm^3, million cubic meter.



f0055 **Figure 10** Population and water demand projection for Dhaka city. Unit for water demand is million liters per day (mld). Source: After Rahman, S. and F. Hossain, 2008: Spatial assessment of water quality of peripheral rivers of Dhaka City for optimal relocation of water intake point. *Water Resour. Manag.*, **22** (3), 377–391, http://dx.doi.org/10.1007/s11269-007-9167-y.

make 245 million liters per day for city water supply." Such an endorsement of our vulnerability assessment approach through an independent pilot-scale study (i.e., earlier we claimed in our study that about 62% of rainfall is potentially an untapped resource for Dhaka) demonstrates the effectiveness of the bottom-up approach as a decision-making tool for the adaptation community. Overall, this study demonstrates that an accurate understanding of the rainfall and runoff modification patterns in the context of rapid land use change (such as urbanization) using a bottom-up assessment approach is critical to forecasting future water resources vulnerability and for designing harvesting schemes.

s0035 5.40.6 Conclusion

p0125 This study explored the water resources vulnerability for Dhaka city in the context of rapid land use change that compromises the sustainability of its renewable water resources. Using observational evidence, it found that rainfall experienced strong spatial signature, where the region downwind of the city seemed to receive statistically higher rainfall than the upwind region. Direct physical attribution to rapid urbanization of Dhaka city was not possible for the 28 July 2009 storm that broke a 53-year record. In the wider context of the country, the study also found that urban regions in general receive less rainfall than the nonurban regions.

p0130 As a future extension of this study to pinpoint more specifically the plan for sustainable water resources development, atmospheric modeling combined with investigation of local convective initiation should be carried out. Such a study would help policy planners understand if future urbanization may alter the frequency and intensity of heavy rainfall events in the context of a changing climate. The CN model used for urban runoff in this study provides only an external description of water availability (e.g., Dhaka city as the control volume). More sophisticated models for urban runoff such as Storm Water Management Model (SWMM) or MIKE-URBAN could be used for detailed planning in the near future. Such models take into account the topography and urban drainage network consisting of pipes and open channels and, provide, as a decision-making output, optimal locations for capture of runoff. Such modeled locations can be potential feasibility sites for the Selatar-Bedok-type urban runoff capturing reservoir or for artificial recharge of groundwater. Although this study shows promise for a sustainable water resources development plan for Dhaka city, it is only with such detailed models and further analysis that the design specifications of systems be identified to safeguard the water security of South Asian megacities such as Dhaka.

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