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Sustainability of rainwater management and land-use compliance – a case of greater Dhaka

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Abstract: Land-use change due to urbanization in the capital city Dhaka has resulted high population density, reduced green space, uneven rainfall distribution, increased runoff, reduced recharge, and water stress with an imbalance in the water cycle with quality and quantity of groundwater (GW). Acute reliance on GW for water demand management in Dhaka is yet to be complemented by rainwater despite high average annual rainfall and legal compliance for its use. The mandated rainwater harvesting (RWH) and GW recharge provisions can be easily integrated in greater Dhaka's new urbanization having land occupancy 300 m^2 and above. This study identifies the sustainability issues of rainwater management with a case study area in greater Dhaka applying GIS and using land-use compliance tools i.e., FAR (Floor Area Ratio) and MGC (Maximum Ground Coverage). The proposed land-use change explicates the possibility of 50% runoff reduction through an implementable rainwater management option with RWH from roof catchment and GW recharge from unpaved area. The potable and non-potable water saving efficiency reduces significantly if the urban growth is planned with higher FAR. Overall sustainability of rainwater management signifies a lower FAR 1 to 1.5 for greater Dhaka's urban growth and enforcement of decentralized rainwater management compliance.

Keywords: land-use compliance, rainwater management, rainwater harvesting (RWH), sustainability, water demand

1. Introduction

Water is a finite resource and rainfall remains the origin of all water sources. It is serving as the critical link between the climate system, human society and the environment towards achieving sustainable development [1], [2] and making sustainable cities [3]. The world is now more than half urban [4]. By 2050, more than two third of the global population will be living in cities with significant water stress [5]. Water management in the megacities of developing countries are getting increasingly complex due to increasing population, excessive water demand, over-exploitation of groundwater (GW) resources, lack of sustainable water management practices and capacity to deal with the rapid change [6]-[9]. Climate change will add further complexities in terms of water accessibility and water quality due to population growth, urbanization, and land-use change [10]-[12].

With the highest population density among the megacities of the world, the observed population of the capital city Dhaka was 21.006 million in 2020 [1]. Moreover, Dhaka is projected to be the 4th largest megacity in the world after Delhi, Tokyo and Shanghai with 28.076 million by 2030 and 31.234 million by 2035 [1], [13]. The revised total area of Dhaka Metropolitan Region (DMR) as per the GIS database is around 1528 sq km [14]. The primate city Dhaka has spatially extended and split into six regions to meet the dwelling need of middle-and high-income households and ensure sustainable urbanization with livable density as opposed to high density urban growth in the central region of Dhaka [14]. Floodplains, healthy green space [15] and natural drainage system both in central and peripheral greater Dhaka are disappearing due to unplanned urbanization and land-filling [16]-[18].Urban water management in central Dhaka is not secured and resilient due to lack of conservation and use or reuse of non-traditional water resources. More than 78% of the water demand and supply is met from GW with an aquifer depletion rate 2 to 3m every year [19].

Rainwater, a promising non-traditional water resource is not widely used in the urban context of Bangladesh [20].Rainwater harvesting (RWH) is in practice in Bangladesh since 1984 in the coastal areas to a limited scale for drinking purpose only[21], [22]. Despite different initiatives, it remains unrealized in Dhaka or any other urban areas of Bangladesh. Many national and international studies have recognized the multiple benefits of rainwater management in conserving water; minimizing runoff, urban flooding, and GW depletion through aquifer recharge, and achieving sustainable development [23]-[26]. The known challenges of RWH systems for urban areas include the social awareness, acceptance and attitude towards using rainwater as it is a free resource, lack of technical knowledge and standardization for its implementation, significant space requirement for the storage facility in costly urban land, maintenance aspects of the system, economic constraints, funding mechanism and stakeholders' engagement in making it a reality[27]-[32]. However, global interest on the use of RWH systems is increasing and being implemented in cities of developed world but not widely [33]. Arguably, it is unfeasible and expensive in densely populated areas of developing-world cities because of low per capita roof area, limited space and cheap mains water[34]. In fact, Dhaka and other urban areas that have high average annual and monsoonal rainfall, well planned centralized and decentralized storage systems for RWH in all new urbanization could reduce the cost of water supply, increase water saving efficiency and ensure sustainability of the urban development[23], [35], [36]. As a low cost technology, decentralized system may help improve the access to water and sanitation at the local level [37], [38].

The Building Construction Rules 2008 [39] provides the basis for urban development control of Dhaka through 'Maximum Ground Coverage' (MGC) and 'Floor Area Ratio' (FAR). Bangladesh National Building Code (BNBC) 2020 [40] has mandated regulations for rainwater management with rooftop RWH and artificial GW recharge. Application of regulations into functioning form by municipal or water authorities isyet to be observed. Rainwater management should be integrated as part of overall urban water management plan to realize the goal of water supply and sanitation as envisioned in Delta Plan 2100 [41] and towards achieving SDG 6 and 11. Any new urban development in Dhaka retains the potential to integrate the RWH systems and requires only compliance and monitoring of the stakeholders.

Greater Dhaka's eastern region is very close to central Dhaka. There are two new major urban growths as per DAP 2016-35 [14] in the eastern region of Dhaka. One of the urban growths, 'Jolshiri Housing' has been planned as an independent township with all the urban infrastructure, amenities and facilities for a fully functional urban living by 2040 and beyond. Proposed land-use change intends to make it a modern eco city to accommodate about 9, 18,057population on an approximately 2133 acres (8.633 km^2) of land[42].

Effective land-use planning is increasingly important for all new urban growths in greater Dhaka to maintain the water cycle balance and help achieve urban sustainability. This study attempts to explore the land-use plan of the study area and assess the sustainability of rainwater management during complete urbanization by categorizing the land-use plan into useful runoff generation components. Assorted options of rainwater management have been assessed using the legal compliance of rainwater management and suitability of the land-use. Existing urban land-use compliance i.e., MGC and FAR have been used to contest the sustainability of rainwater management of the study area. In doing so, most dominant land-use type of the urban growth has been critically assessed to ascertain the overall sustainability of urban rainwater management due to land-use compliance.

2. Materials and Methods

2.1 Location and hydro geological settings of study area

The study area is located at greater Dhaka and lies between latitude 23°47′5″N to 23°49′15″N and longitude 90°29′5″E to 90°31′3″E. It is at the center of the eastern region of greater Dhaka. The area is enclosed by the River Balu in the west and the River Shitalakkhya in the east (Fig 1).The study area approximately 8.633 sq km of land is reclaimed from low-lying agricultural land to residential land with sand-filling. About 98% of the reclaimed land of the study area was cultivable low-lying land. The soil of the filled land after development represents hydrologic soil group ‘A’ which is adequately deep and well-drained sands with low runoff potential and rapid infiltration rate greater than 7.5 mm/hour. Areas planned for residential development are expected to have an average elevation of 8 to 8.25m SOB reference level. Other surrounding areas are generally low, flat, and flood-prone and elevation varies from 2 to 13 meter above mean sea level [42].

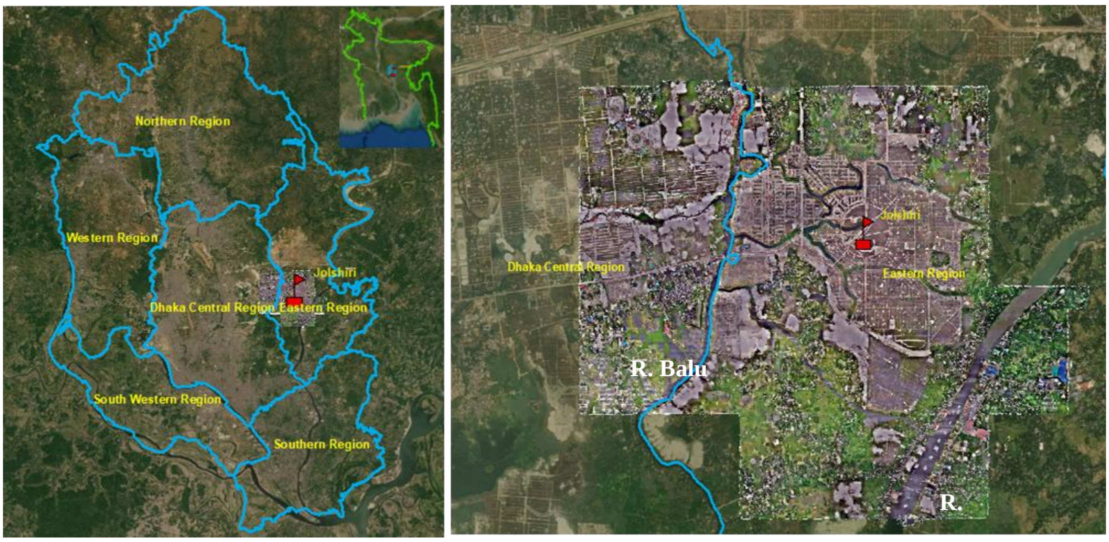

Figure 1: Regional boundary of greater Dhaka and drone image of study area location (Source:

2.2 Land-use change

The land area has been divided into 17 sectors with residential, commercial and institutional areas and quite ready for infrastructure development works. The dominant land-use occupancy relates to 8,379 residential plots with 335 square meter (sqm) or 3600 square feet (sft). The residential area covers around 33% of the total land-use. The next largest land-use is around 31% for development of roads and pedestrians followed by lake around 10%. The key land-use details are at Table 1.

Table 1: Key Land-use Components [42]

Land-use Category	No. of Plots	Area in sqm	Percent
Residential • @ 335 sqm (3600 sft) : 8379 • @ 669 sqm (7200 sft) : 21 • @ 1338 sqm(14400 sft) : 5 • @10825 sqm High-rise Apartment Blocks : 6	8420	2786554	32.277
Commercial	212	289759	3.356
Education Establishments	52	569838	6.601
Healthcare Facilities	13	65518	0.759
Sports Facilities	24	357285	4.139
Amusement & Recreation	21	629290	7.289
Religious & Community Services	32	96525	1.118
Utility Establishments & Installations	22	126160	1.461
Other Features	43	100900	1.169
Lake	-	895679	10.375
Roads & Pedestrians	-	2715613	31.456
Total		8633167	100

2.3 Population projection

The population of the proposed urban growth will increase with the gradual change in the land-use. The design population of the urban growth is approximately 9, 18,057 during full-scale urban growth. The expecteddensity is 1, 06,341 p/sq km or 1063 p/ha or 430 p/acre[42]. As the future population of DMR area for the year 2035 is projected to be about 26 million, DAP 2016-35 proposes to maintain an average urban density at 121 p/acre or 300 p/ha or 30,000 p/ km^2 level in order to ensure livability across all regions of greater Dhaka except the Dhaka Central region[14]. Considering the livable density 121 p/acre,the residential population is likely to be 3, 00, 000including40,000 (floating population) during full-scale urban growth by 2040 and beyond. The design population and the livable population intensity and density vary remarkably. The livable population as per DAP 2016-35 [14] is around one third of the design population.

2.4 Water demand

Per capita water demand is directly related to the socio-economic status of the living population, type of habitants, population of the area and public facilities. Total water requirements for the township as a whole, mainly for domestic purposes is based on the projected population. Per capita water consumption is at Table 2 as per BNBC 2020 [40].The living population of the study area belongs to middle income group and per capita water consumption is considered as 135 lpcd with restricted facility for the entire urban growth. Though per capita water consumption for different categories of people for different types of domestic, recreational, and commercial uses vary significantly, the per capita water consumption is kept same for the city planning. For residential buildings, the household requirement is based on a family size of 5 (five).

Table 2: Water Consumption for Domestic Purposes in Residential Buildings (Metropolitan Cities/City Corporation Area/District Towns) [40]

Water Consumption	Full Facility (lpcd)	Restricted Facility (lpcd)
High income group:		
Single family dwelling (with garden and car washing)	260	200
Big multi-family apartment/flat (> 2500 sft)	200	150
Middle income group:		
Officers' qtr./Colony and moderate apartment (< 2000 sft)	180	135
Small building/staff qtr. and small apartment (< 1500 sft)	-	120

According to the water use and consumption for domestic purposes in a residential building (Table 3), daily non-potable demand is considered for only toilet flushing and cleaning house which is 30% of daily water demand i.e., 40.5 lpcd. Individual annual potable water demand is 49.275 m^3 or kilo liter (kl) and non-potable water demand is 14.7825 kl. Monthly potable water demand per household is 20.25 kl and non-potable demand is 6.08 kl. Considering the two population scenarios of the urban growth, projected water demand for the design population will be 45237259 kl/yr and for the livable population as per DAP 2016-35 will be 14782500 kl/yr.

Table 3: Water Use and Consumption for Domestic Purposes in Residential Buildings [43]

Use	Consumption (lpd)	Consumption (%)
Drinking	5	3.7
Cooking	5	3.7
Bathing (including ablution)	55	4.74
Washing Clothes	20	14.81
Washing Utensils	10	7.41
Cleaning the House	10	7.41
Flushing of Toilets	30	22.22
Total for Urban Areas	135	100

2.5 Land-use compliance

FAR and MGC are the primary planning tools for urban development control. FAR is the ratio of accumulated floor areas against the given size of a plot or area. New building construction rules were promulgated for Dhaka in 2008 [39]. Since then a notable shift from low-rise to high-rise residential building is common in Dhaka city due to the advantage of FAR. Urban density policy is usually implemented through FAR. MGC is linked to FAR in a way that allows an unpaved open area within the land occupancy for GW recharge. All urban development in Dhaka must comply with the stated rules in Table 4. The percentage imperviousness of the land surface due to urbanization depicts the type of area with density of development [40]. Land-use compliance is approved and monitored by capital development authority, i.e. RAJUK (Rajdhani Unnoyon Kartipakkha).

Table 4: FAR and MGC for Construction of Residential Building at Dhaka [39]

Land Area of Plot		Road Width, m	FAR	MGC (%)
268 to 335 sqm	2880 to 3600 sft	6	3.5	62.5
335 to 402 sqm	3600 to 4320 sft	6	3.75	60.0
603 to 70 sqm	6480 to 7200 sft	6	4.25	55.0
1206 to 1340 sqm	12,960 to 14,400 sft	6	5.25	50.0
Above 1340 sqm	Above 14,400 sft	9	5.5	50.0

2.6 Rainwater management compliance

Rainwater management is directly linked to runoff management. BNBC 2020 articulates the details of rainwater management in all urban growths with the provisions for planning, design and installation of rainwater management systems in buildings. It states that 'every building proposed for constructing on plots having extent of 300 sqm (3229 sft) or above shall have facilities for conserving and harvesting rainwater'. The building means all residential, commercial, business, education institutes, etc. Rainwater should be conserved and used in all useful purposes related to use of water. It suggests two major aspects of RWH: (i) rooftop RWH, and (ii) artificial GW recharge including the treatment requirements for potable and non-potable rainwater for harvesting, flushing out first rainwater, storing and precautions for rainwater storage and GW recharge. However, there is no standardized manual for storage and roof area to be used for RWH as per the land-use compliance. The rainwater management in general, lacks compliance by the stakeholders.

2.7 Average annual rainfall

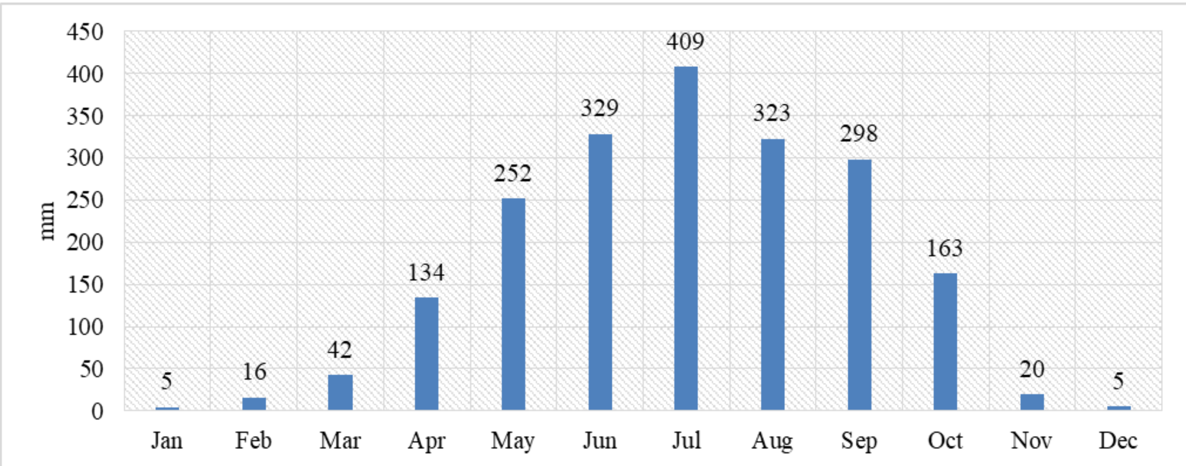

Figure 2: A- 25 year average monthly rainfall for Dhaka (1995 to 2020)

Sustainability of rainwater management largely depends on the availability of rainfall and variability due to climate change impacts. However, the observed and projected climate change impacts as per IPCC 2022 [1] for Dhaka includes the likelihood of rising temperature and heat waves with high risk of flooding and medium risk of extreme rain and water scarcity (drought). The average annual rainfall in Dhaka is about 2000 to 2200 mm and 70% to 75% occurs during the monsoon season (June to October) with high variability [23], [44]. The annual average rainfall of 25 years (1995-2020) of Dhaka from Bangladesh Water Development Board (BWDB) is about 1995 mm with the highest as 2892 mm and lowest as 1365 mm. The annual average monsoon rainfall is about 1358 mm. The 25-year monthly average rainfall is given at Fig 2.

3. Methods

The urban catchment has been categorized with rainwater management potentials by applying GIS and using land-use rules. Runoff potential of the land-use components have been estimated following the rational runoff equation and rainwater management codes illustrated in BNBC 2020 [40]. Monthly balance of rainwater management from the most dominant residential land occupancy is used to identify the potential of potable and non-potable water demand met from roof catchment including its overflow ratio and water saving efficiency. Sustainability of rainwater management of the urban growth has been ascertained in general, through runoff reduction potential by RWH and GW recharge, water saving efficiency, water demand management due to population intensity and density, and in particular, with the effectiveness of land-use compliance, i.e., implication of FAR and MGC as two key urban development control tools for the given population scenarios.

3.1 Key run off components due to land-use change

Catchment areas as runoff components due to land-use change are categorized as paved, unpaved and water body by applying GIS and using MGC and FAR in all structural components (Fig 3). The roof catchment for each type of land-use is considered with maximum floor or roof area derived from MGC and the highest FAR. The land-use compliance reveals a landscape of 61.55% paved, 28.83% unpaved and 9.62% water body during full-scale urban growth. The identified 61.55% imperviousness of the area depicts a high density residential development [40]. Land-use type and catchment areas are presented at Table 5. Paved area includes two types of runoff catchment: (i) the roof of all residential, commercial, business, educational, utility and community services buildings and (ii) the roads and other hard standings. Unpaved area as third runoff component includes the catchment of all

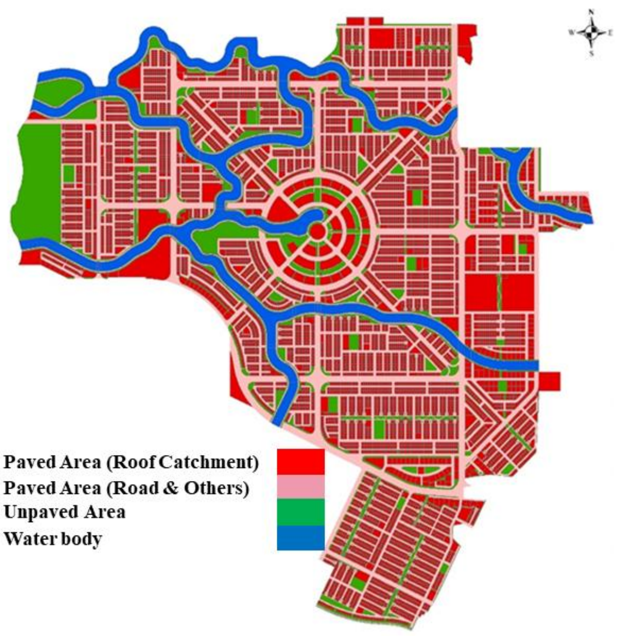

Figure 3: Major land-use components of study area

open space, urban greenery, parks, playground, and golf course without any hard surface and from where water is easily rechargeable. The fourth component, water body includes the existing canal networks or lake within the area.

Table 5: Land-use type and catchment area [42]

Category of Land-use		Area in sqm
Paved		5313432
i.	Roof Catchment	2236916
ii.	Road & Other Paved Area	3076516
Unpaved		2489033
Water body		830702
Total		8633167

3.2 Runoff estimation

Runoff is principally the water flowing away from a catchment area after rainfall and dependent on the rainfall intensity, area of the interception surface and the nature of the catchment material. Both paved and unpaved catchment areas generate runoff. Paved surfaces have greater retention capacity of water as opposed to unpaved surface. In all calculations for runoff estimation, runoff coefficient is used to account for losses due to spillage, leakage, infiltrations, catchment surface wetting and evaporation, which ultimately results into reduced runoff. The runoff coefficient for various surfaces is given in Table 8.In this study, runoff coefficient for all paved surface is considered 0.8 and for unpaved surface 0.3. The available rainwater with RWH potential is estimated by the system assessed through the rational equation:

$$\mathbf{S = A*R*C} \quad (1)$$

Where, S = Mean rainwater supply in m^3, A = Surface area of catchment in m^2, R = Mean annual rainfall in mm/year, C = Run-off coefficient

Table 6: Default values for the runoff coefficient [45]

Type of Catchment	Coefficients
Roof Catchments	
▪ Tiles	0.8 – 0.9
▪ Corrugated metal sheets	0.7- 0.9
Ground surface coverings	
▪ Concrete	0.6 – 0.8
▪ Brick pavement	0.5- 0.6
Untreated ground catchments	
▪ Soil on slopes less than 10%	0.0 – 0.3
▪ Rocky natural catchments	0.2 – 0.5

3.2 Water saving efficiency

Water saving efficiency is a measure of amount of runoff harvested as a ratio to the total runoff (Farreni et al. [46]. This ‘efficiency’ essentially is a measure of runoff reduction. It means the ratio or percentage or volume of potable water saved or harvested by applying RWH systems against the total demand. However, Briggs and Reidy[47], Imteaz et al. [48], [49] termed 'efficiency' as 'reliability' by which percentage of individual water demand fully met by the RWH systems. In this study, water saving efficiency is considered as the percentage or volume of potable and non-potable water saved from RWH systems against the total water demand.

3.3 Monthly water balance analysis for rooftop RWH

A simple monthly water balance model is used to assess the monthly potable and non-potable water demand management by rainwater from roof catchment. Like other similar studies, Ebenezer & Nsiah [50] and Aladenola & Adeboye [51] quantified the rooftop RWH potential of urban structural roof catchment through a monthly balance model. The method calculates the monthly water supply, demand and storage potential with an overflow ratio due to spillage and size of the storage facility including the water saving efficiency. Overflow ratio is measured as the ratio of volume of rainwater exceeding the storage capacity to the volume of total rainwater. The equation used in calculating the monthly RWH potential from a given roof catchment is:

$$\mathbf{S = I_V + V_R - D_W} \quad \text{(2)}$$

Where, S= Monthly balance from rainwater (m^3), I_V = Initial volume of water in the tank, V_R= Volume of available rainwater in a month (m^3),and D_W= Monthly water demand for a household (m^3)

4. Results and Discussion

4.1 Rainwater management potential of urban catchment

The proposed urban growth provides the opportunities to manage the catchable rainwater as per the structural and non-structural components of the land-use. Alongside, sector wise rainwater can also be managed as per the given land-use. This indeed provides assorted options for rainwater management and the reduction of runoff from the urban catchment. Total runoff from the proposed urban growth is approximately 1, 15, 61,387 kl/yr of which 32% from roof catchment, 41% from road and other paved area, 13% from unpaved open area and 14% in the water body (Fig 4). The total catchable runoff is 99, 04,136 kl/yr excluding the runoff in water body. While considering the percentage of catchable runoff, 48% is from the road and other paved surfaces, 37% from all roof catchment and 15% from unpaved open area. Sector wise runoff potential is given at Fig 5.

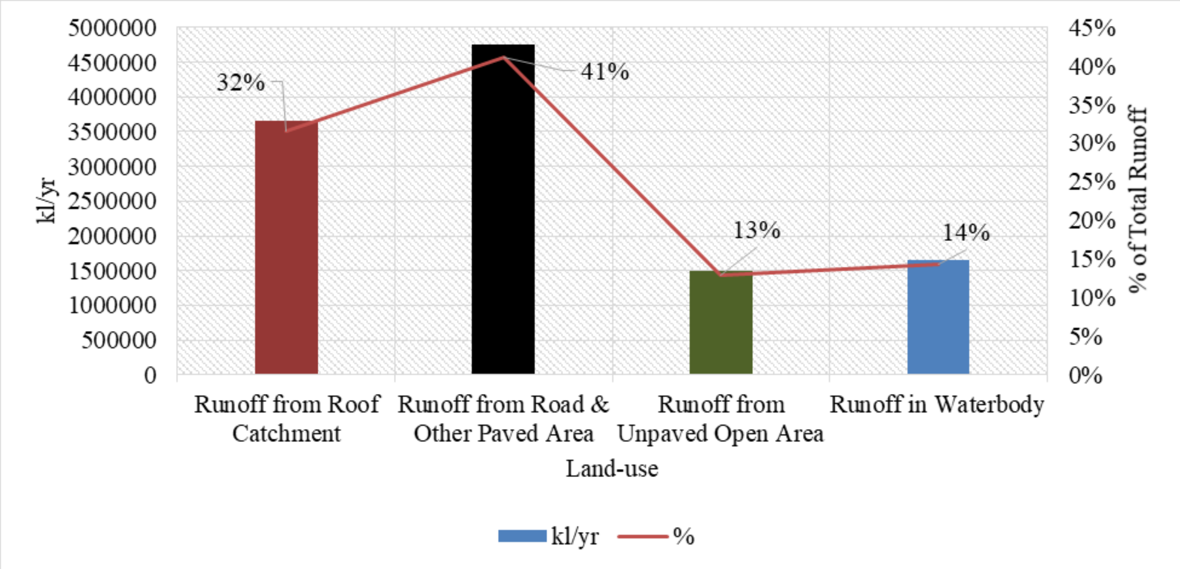

Figure 4: Runoff generation due to land-use change

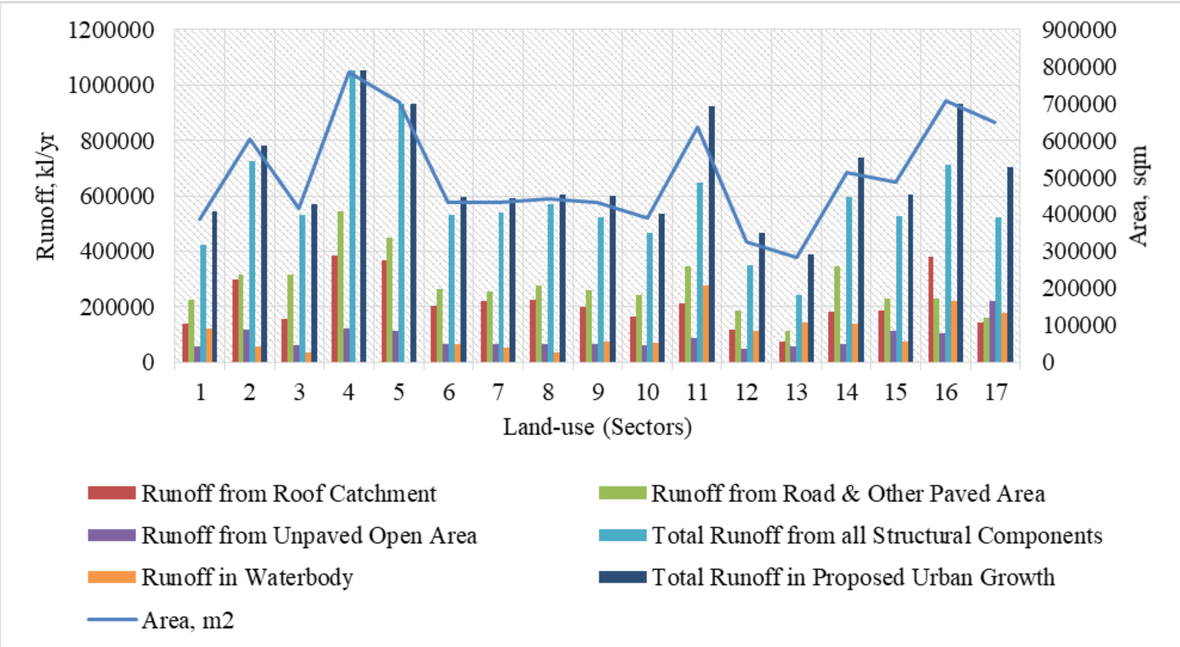

Figure 5: Sector wise runoff generation due to land-use change

4.2 Potential rainwater management options for runoff reduction

Runoff resulted from high intensity rainfall in Dhaka makes the city waterlogged for hours. Typical rainwater management in Dhaka city involves the drainage from all urban catchment to combined sewer system without any harvesting potential or runoff reduction. However, without any runoff reduction, all rainwater as drainage load can be managed by separate storm water sewer system. There will be increased drainage load and cost of drainage management. It is simply a non-compliance to BNBC 2020 in case of rainwater management. The options available for rainwater management following the application and compliance of RWH systems are given in Fig 6and briefly illustrated below as options of runoff reduction due to land-use change, extreme rainfall events and suitability of the land.

Option 1**(**GW Recharge from Unpaved Open Area) provides the scope for15% runoff reduction from the total runoff due to GW recharge with no water saving efficiency of potable water demand. As the land is sand filled, there can be easy infiltration of water from the unpaved open area through natural recharge and swales. However, the GW recharge can be augmented through artificial recharge by wells and pits. With partial compliance to rainwater management as per BNBC 2020, significant drainage load needs to be managed separately through storm sewer system.

Option 2(Water Demand Management from Roof Catchment) reduces approximately 37% runoff can from the total runoff by RWH from roof catchment. The RWH system needs to be integrated in each building with individual storage system or facility. All larger plots such as residential, commercial, business, academic institutions and other service facility should plan for large storage capacity for storing rainwater and meet the potable or non-potable demand. The dominant residential plots with 335 sqm would face difficulty in storing the rainwater mainly because of space limitations. However, large underground reservoir can be constructed to store the rainwater for both potable and non-potable use. If rainwater is used for non-potable demand, comparatively smaller storage can serve the purpose. Excess rainwater beyond the storage capacity of individual building can be managed with artificial GW recharge with well and pits, or drained to storm sewer system, and or drained for RWH to centralized reservoir or to existing canal networks or part of the canals with pollution prevention. The system will have potable water saving efficiency. As the urbanization in the study area is progressing, rooftop RWH systems can be easily integrated to have sustainability in overall urban water management. This option complies with BNBC 2020.

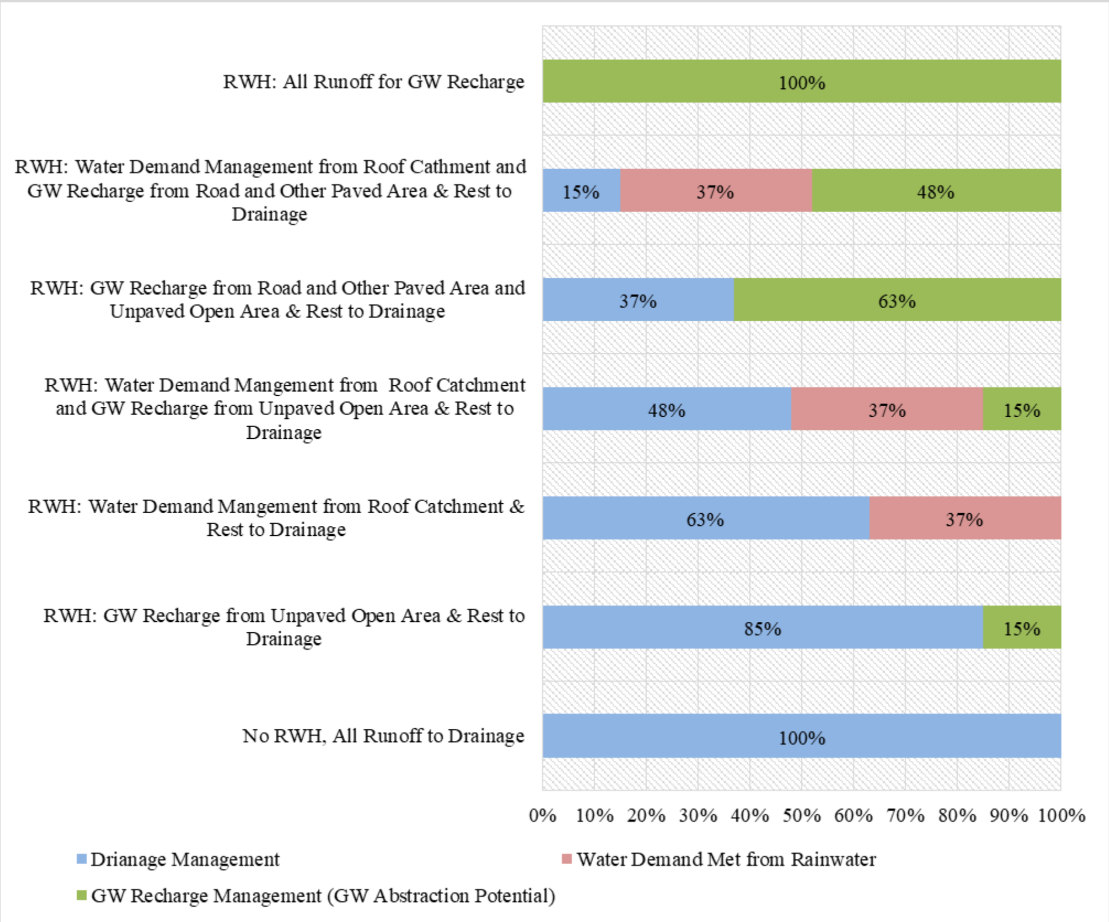

Figure 6: Rainwater management options for runoff reduction

Option 3(Water Demand Management from Roof Catchment and GW Recharge from Unpaved Open Area) reduces around 52% runoff from the total runoff. This option can be easily integrated as mentioned above in option 1 and 2 with significant potable water saving efficiency, volumetric reliability, aquifer recharge, and sustainability. This option also complies with BNBC 2020 for rainwater management.

Option 4(GW Recharge from Road and Other Paved Area and Unpaved Open Area) provides opportunity to reduce approximately 63%runoff from the total runoff. This option needs extensive artificial GW recharge by wells and pits and natural recharge through swales or other means. There will be no potable water saving efficiency. However, during extreme rainfall events runoff reduction will be difficult in the absence proper drainage facility. This option partially complies with BNBC 2020.

Option 5(Water Demand Management from Roof Catchment and Artificial GW Recharge from Road and Other Paved Area) increases the runoff reduction potential around 85% from total runoff. Though this option reduces runoff significantly and complies BNBC 2020, it needs space management to incorporate recharge pits and wells and risk remains for runoff reduction without proper drainage facility in case of extreme rainfall events.

Option 6(All Runoff as GW Recharge) provides an opportunity to reduce 100% runoff from the urban catchment. It needs significant space management for recharge wells, pitsand swales. Risk remains for runoff reduction during extreme rainfall events. However, this does not account for any potable water saving efficiency and partially complies with BNBC 2020 in case domestic rainwater management.

4.3 Water Saving Efficiency with RWH from Roof Catchment

Water saving efficiency increases by augmenting RWH potential. If all catchable rainwater could be harvested, annual potable water demand of approximately 2, 00,000 population could be met with 135 lpd and three times more population could be met with non-potable water demand with 40.5 lpd. Available rainwater is too short to meet the daily potable and non-potable demand of the design population. However, two third of the potable demand and more than non-potable demand of livable population could be met with all harvested rainwater annually. The water saving efficiency of urban catchment from rooftop RWH is given at Fig 7. The water saving efficiency in terms of potable water demand varies from 8% to25% and 27% to 82% for potable and non-potable water demand for the design and livable population respectively. Water saving efficiency as a measure of sustainability increases in case of livable population density.

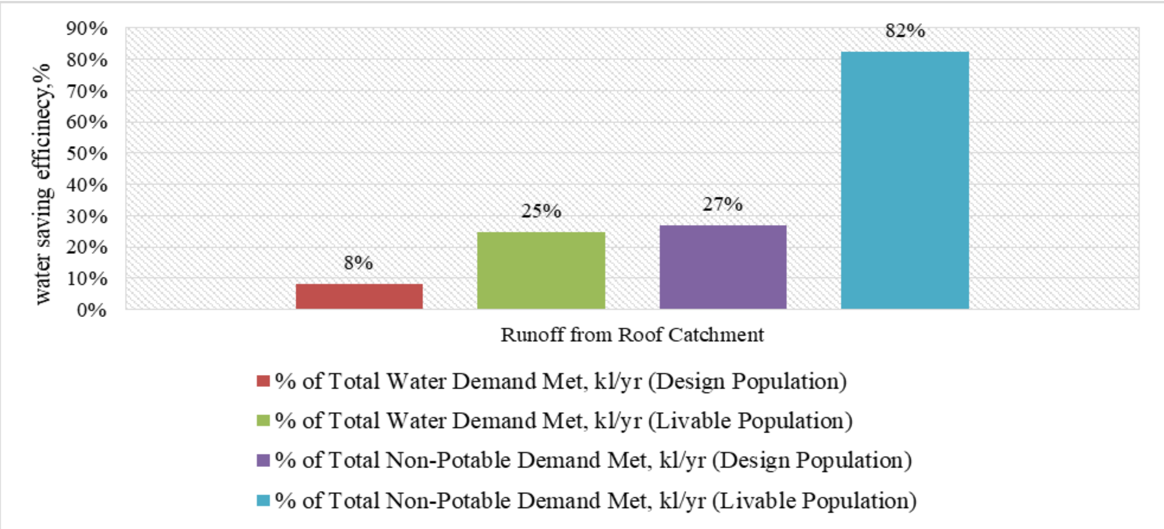

Figure 7: Water saving efficiency from all roof catchment

This water saving efficiency is subject to rainwater storage capacity of all types of buildings. All commercial, business, academic institutions and community services need more non-potable water as opposed to potable water which can be easily managed by large storage facility in underground reservoirs. However, residential buildings can also plan for big underground reservoir to meet both potable and non-potable demand with RWH systems. The efficiency remains uncertain due to variability of rainfall and climate change impacts.

4.4 Feasible rain water management option for the land-use change

Considering the suitability of land, runoff reduction, extreme rainfall events due to climate change, water saving efficiency and legal compliance to rainwater management as per BNBC 2020, option 3fares better than others where more than 50% runoff can be reduced with potable or non-potable water demand management (3656962kl/yr) along with GW recharge provision. Overall runoff reduction leaves a scope for the urban growth to sustain annually with rainwater and GW for limited population intensity or density. The maximum and minimum GW recharge potentials(Table 8) provide the guidelines for maximum and minimum annual GW abstraction prospect from the proposed urban growth. Fig 8 provides the overall annual rainwater management and water supply requirement due to impending land-use change. Land-use change as per the design and livable population respectively provides the possibility for 3% to 10% annual GW abstraction with minimum GW recharge provision (1489686 kl/yr) and 14% to 42% with maximum GW recharge provision (6247174 kl/yr)with all rainwater from road and other paved areas harvested for GW recharge. During full-scale urban growth, minimum 58% to 86% and maximum 90% to 97% water supply will be required for the proposed urban growth respectively for the livable and design population.

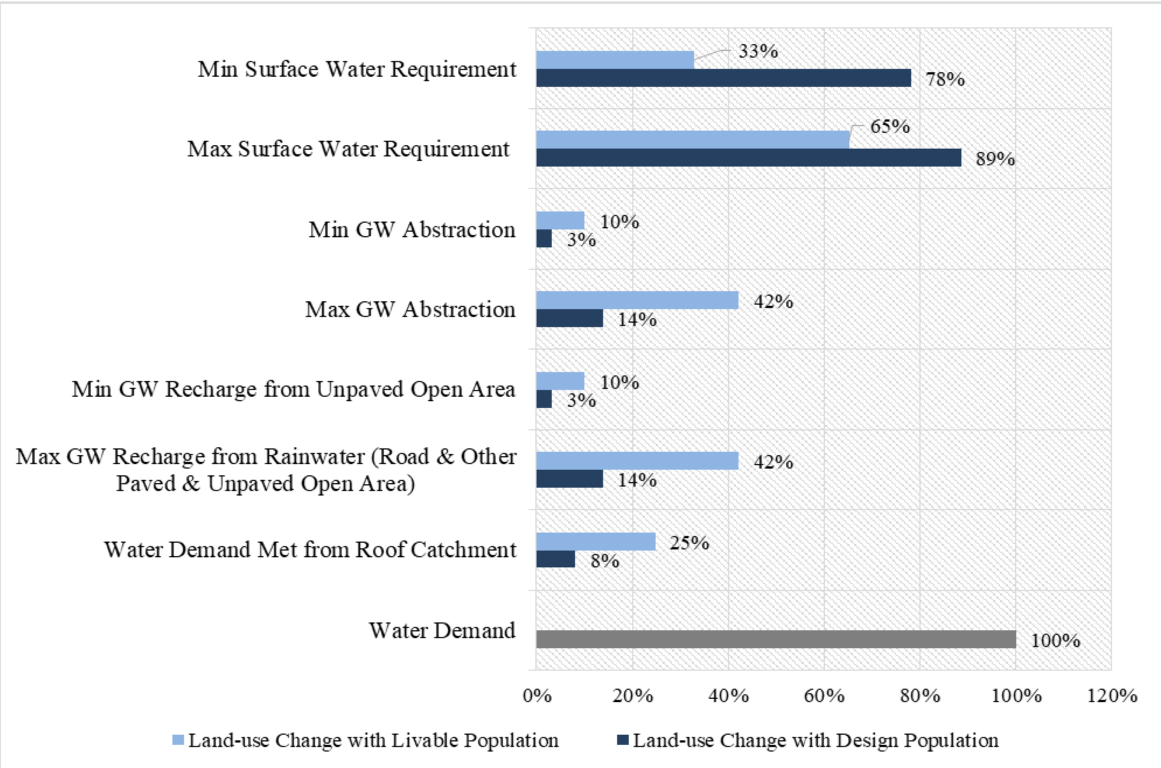

Figure 8: Rainwater and overall water demand management

4.5 RWH potential from individual residential roof catchment

The proposed urban growth has the maximum land occupancy (8379 plots) with 335 sqm.As per the land-use compliance, a 335 sqm plot will have maximum FAR 3.75 if the roadway width is more than 6 meter. So the built area will be 1256 sqmby multiplying FAR with land area and the floor area not more than MGC

(62.50%) will be maximum 209 sqm. Table7 shows the RWH potential in terms of number population could be served with potable and non-potable water demand per day from one residential building with three types of land occupancy where roof areas are considered 200, 300 and 600 sqm against the actual roof area of 209, 384 and 669 sqm respectively. Following the monthly water balance model, potable and non-potable demand management from rainwater for a 200 sqm roof catchment with one household (5 persons/household) is at Table 8.

Table 7: RWH potential of buildings with different land-use occupancy

RWH Potential of Residential Building with Land Occupancy	MGC	Considered Roof Area, sqm	Annual Avg Runoff, kl	Potable Water Demand Met/day (No of pop)	Non-potable Water Demand Met/day (No of pop)
335 sqm	0.625	200	319.2	6	22
669 sqm	0.575	300	478.8	10	32
1338 sqm	0.500	600	957.6	19	65

Table 8: Monthly water balance for 200 sqm roof catchment in 335 sqm land occupancy

Monthly Rainfall, mm	Annual Avg (1995-2020), mm	Monthly Volume of Rainwater, kl	Potable Water Demand, kl	Monthly Balance, kl	Non-potable Water Demand,kl	Monthly Balance, kl
Jan	5	0.76	20.25	-19.49	6.08	-5.3
Feb	16	2.60	20.25	-17.65	6.08	-3.5
Mar	42	6.76	20.25	-13.49	6.08	0.7
Apr	134	21.41	20.25	1.16	6.08	15.3
May	252	40.33	20.25	20.08	6.08	34.3
Jun	329	52.58	20.25	32.33	6.08	46.5
Jul	409	65.37	20.25	45.12	6.08	59.3
Aug	323	51.65	20.25	31.40	6.08	45.6
Sep	298	47.74	20.25	27.49	6.08	41.7
Oct	163	26.05	20.25	5.80	6.08	20.0
Nov	20	3.12	20.25	-17.13	6.08	-3.0
Dec	5	0.82	20.25	-19.43	6.08	-5.3
Total	1995	319.22	243	76.22	72.90	246.3
Average	166	26.60	20.25	6.35	6.08	20.5

In case of potable water demand (Fig 9), total monthly shortfall is 87.19 kl of rainwater and tank size should be around 107.44 m^3 or 110 kl to meet the demand during dry periods for 5 months (Nov-Mar) for a single household. Without considering the dry period, 21 kl capacity tank can meet the demand for 7 months (Apr-Oct) with a water saving efficiency of approximately 58%. Larger tank for storage is likely to be difficult to place in the smaller land area or occupancy unless the reservoir is constructed underground.

In case of non-potable water demand (Fig 10), 23.28 m^3 or 24 kl tank can meet the annual demand including the reserve for dry periods of four months (Nov-Feb) for a household. However, approximately 6 m^3

or 6 kl tank can meet the non-potable demand for 8 months (Mar-Sep) with a water saving efficiency of 66%.

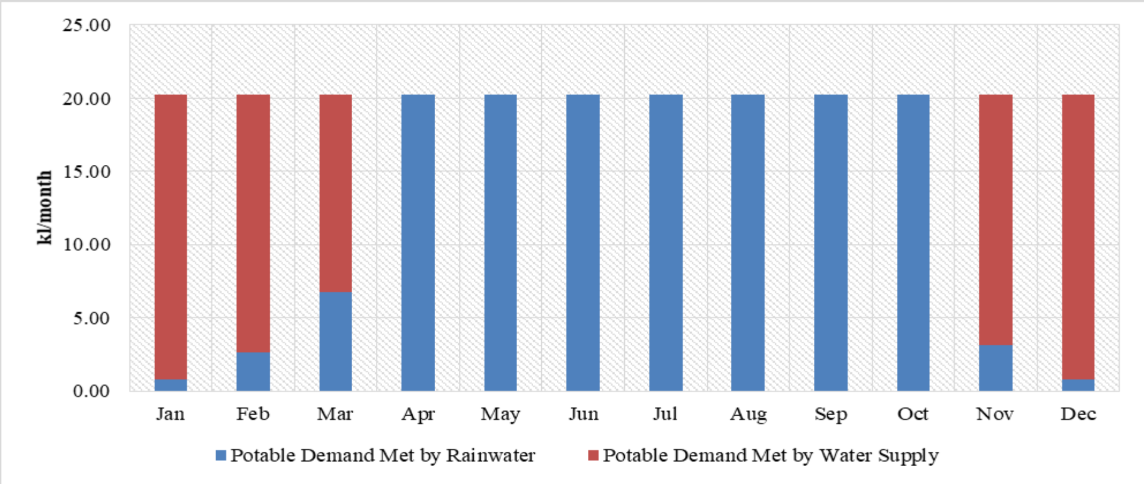

Figure 9: Monthly potable water demand met by rainwater for a single household by 200 sqm roof

Monthly overflow ratio (Fig 11) for the given tank size for both potable and non-potable demand management may be either managed by adequate storage facility, and, or by recharge pits, accumulated in separate centralized storage facility or drained to storm sewer network. The high overflow ratios 69% and 91% are during the month of July for the tank size 21 kl and 6 kl for potable and non-potable water demand management respectively for a single household.

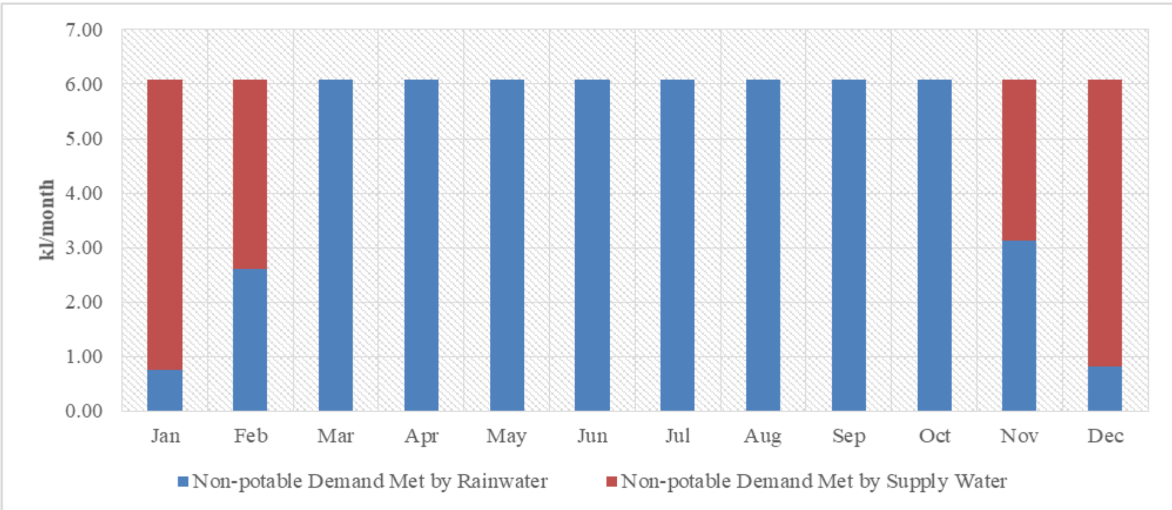

Figure 10: Monthly non-potable water demand met by rainwater for a single household by 200 sqm roof catchment

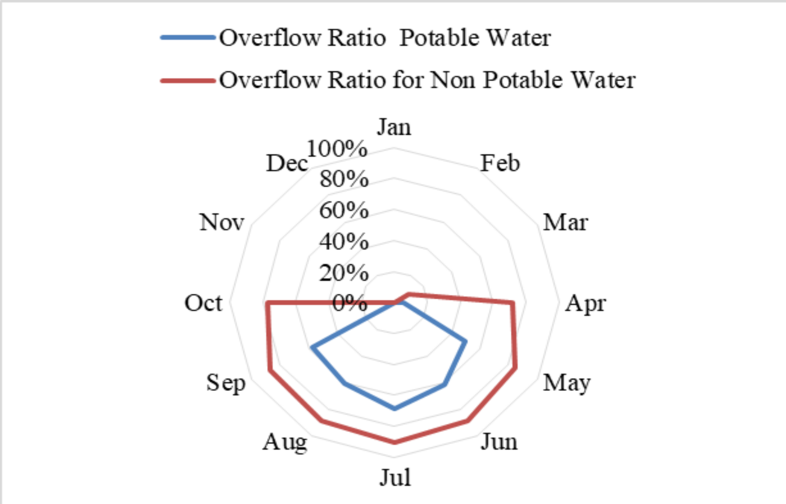

Figure 11: Monthly overflow ratio for both potable and non-potable water demand met by rainwater for a single household by 200 sqm roof catchment

4.6 Implication of land-use compliance for rainwater management

The land-use compliance tool MGC ensures GW recharge potential of any land-use occupancy and FAR limits the total buildable floor area and the population density as number of households in a building. As the urban growth has the maximum land-use occupancy with 335 sqm, the maximum floor area with the highest FAR 3.75 will be 1256 sqm. If 209 sqm is kept in each floor, there can be 1256/209=6.00 floors without ground floor and balcony area. For185.8 sqmin each floor, there can be 6.75 floors, for 167.2 sqm7.50 floors, for148.6 sqm8.43 floors and for 139.4sqm9.00 floors without ground floor and balcony area. Table 9 shows the likely number of maximum households due to increasing FAR in a 335 sqm land occupancy following the existing land-use compliance for Dhaka.

Table 9: Maximum and minimum number of households in a 335 sqm land occupancy

FAR	@104.5 sqm in 209 sqm floor/roof area	@ 92.9 sqm in 185.8 sqm floor/roof area	@83.6 sqm in 167.2 sqm floor/roof area	@74.3 sqm in 148.6 sqm floor/roof area	@69.6 sqm in 139.4 sqm floor/roof area
3.75	12	14	15	17	18
3.5	11	13	14	16	17
3.25	10	12	13	15	16
3	10	11	12	14	14
2.75	9	10	11	12	13
2.5	8	9	10	11	12
2.25	7	8	9	10	11
2	6	7	8	9	10
1.75	6	6	7	8	8
1.5	5	5	6	7	7
1.25	4	5	5	6	6
1	3	4	4	5	5

Considering the maximum household 18 with the highest FAR 3.75 and minimum household 3 with the lowest FAR 1, population intensity in a residential building varies 6 times the population intensity with the lowest FAR. For varying floor or roof area and the number of households, water demand increases significantly due to increasing FAR (Fig 12).With the increasing FAR and household number, 23% reduction in RWH potential is observed due to reduction in roof area. In fact, higher FAR increases the water demand and reduces the RWH potential from roof catchment. With the lowest FAR 1, maximum household number varies from 3 to 5 and water demand increases around 45%. With the highest FAR 3.75, household number varies from 12 to 18 and water demand increases around 50%. Households with the lowest FAR to the highest FAR, the water demand increases around 554%. With the lowest to highest FAR, percentage increase in daily water demand for maximum households in a 335 sqm plot with 104.5 sqm/household with a floor or roof area 209 sqm is 67%.As higher FAR corresponds to higher water demand, annual or monthly rainwater management from residential roof catchment appears quite insufficient and unsustainable to meet the potable or non-potable water demand. However, it can complement the overall water demand. In fact, sustainability of rainwater managementin meeting the water demand of the urban growth reduces with increasing FAR due to reduction of per capita roof area and increase in population intensity. Lower FAR within 1 to 1.5 can contribute towards achieving sustainable urban water management with rainwater and ensure livable population density as per DAP 2016-35 [14].

5. Conclusion

Water stress is now common to many countries and obvious in many megacities of the world including Dhaka. The pace of urbanization, risks of climate change, high population intensity and water demand in cities will only be growing with time. The potential of rainwater as an alternative water resource is now looming large across the globe. Dhaka, the megacity is expanding outwardly from the known core city Dhaka to meet the dwelling need of high and middle income population with a livable population density. The unplanned urban growth in central Dhaka with the highest population density is now water stressed and depleting the GW resources as the surface water sources are heavily polluted. Despite significant annual average rainfall of around 2000 mm, hardly any urban rainwater management is observed in Dhaka city. The rainwater management for any urban growth is mandated by BNBC 2020. Rooftop RWH and GW recharge provision are now obligatory for any structural development with land occupancy of 300 sqm and above. The legal compliance of rainwater management lacks implementation and monitoring by any municipal authority in Dhaka or any other urban areas of Bangladesh.

Continuous urbanization in greater Dhaka is rapidly changing its original landscape. FAR and MGC are the two urban development control tools govern the land-use compliance for any urban growth of Dhaka. One such urban growth in greater Dhaka is just awaiting its development by 2040 and beyond with a high population intensity and density due to compliance of existing FAR. The existing FAR is unmatched to achieving livable density as envisioned in DAP 2016-35. The livable population density for greater Dhaka confirms the consideration of lower FAR in planning any new urban growth. Given the population scenarios of the proposed urban growth in greater Dhaka, sustainability of rainwater management relies on runoff reduction with the integrated RWH systems for roof catchment and GW recharge following rainwater management compliance as per BNBC 2020. The ascertained feasible option of rainwater management can reduce around 50% runoff and flooding vulnerability of the urban growth acknowledging the legal compliance for rainwater management, land-use suitability and extreme rainfall events due to climate change. The implementable runoff reduction options with RWH from roof catchment and GW recharge provision can also project the overall water demand management of the urban growth with other sources of water.In case of potable and non-potable water saving efficiency, sustainability is largely dependent on the population intensity and density of the urban growth. With the livable population density, significant water demand management is possible from rainwater which meets the requirements for sustainable development of greater Dhaka with respect to urban water demand management.

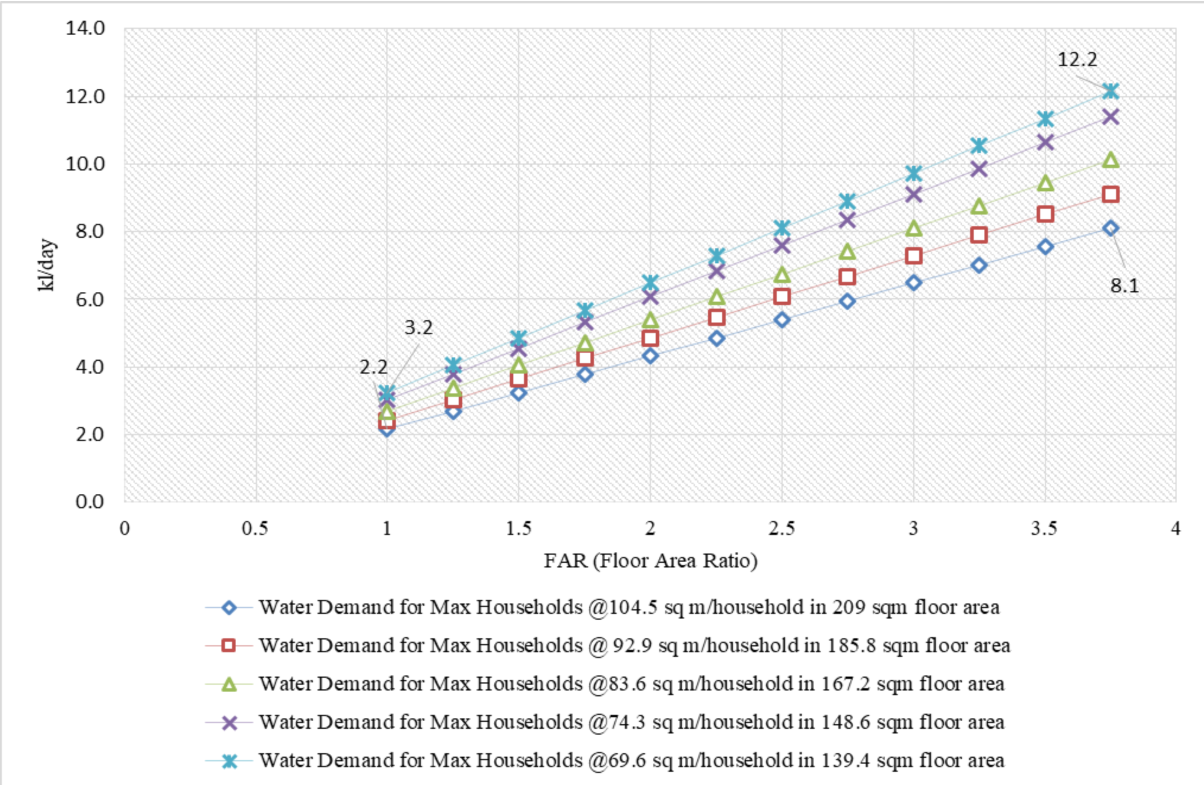

Figure 12: Water demand for varying FAR in a 335 sqm plot

However, the overall water saving efficiency increases in case of non-potable demand management for both the population scenarios, but remarkably reduces with potable and non-potable demand management with design population density.

Sustainability of rainwater management from decentralized individual rooftop RWH is largely contingent upon the roof area as per land-use occupancy, storage facility or the tank size and the residential population intensity. Due to varying land-use occupancy and population intensity, per capita roof area and storage size vary to meet the water demand of the households. The maximum residential land-use occupancy of the urban growth with 335 sqm can meet the annual water demand of approximately a single household and non-potable demand of 4 to 5 households with the availability of average annual rainfall. The given demand can be met with the help of adequate storage facility which needs large size reservoir or tank including space for construction or placement. Due to land-use compliance, increasing FAR increases the population in the urban growth linearly with the increasing household number. Design population of the proposed urban growth validates the consideration of the highest FAR for planning the urban development. In contrast, the livable population corresponds to the FAR in between 1 to 1.5. Higher FAR and high population density poorly contribute in meeting the water demand of the urban growth by rainwater management. Higher FAR reduces the per capita roof area, hence lower the RWH potential. Lower FAR with livable density can ensure sustainability of rainwater as well as urban water management as a whole. In addition, lower FAR can facilitate manageable storage requirement for the rainwater from a roof catchment. For the low impact urban development with climate resilient and nature based options of urban water management, a revised FAR is essential to achieve the sustainability in any proposed and future urban growths in greater Dhaka. Rainwater management is essential at least to meet the partial water demand and to face the extreme events due to climate change in future urbanization. In fact, reduction of FAR is instrumental for the effective implementation of rainwater management in urban development especially in greater Dhaka. Otherwise, the legal compliance of rainwater management will not bring any distinctive change in urban water management scenarioand for planning sustainable cities. In addition, there should be specific implementation guidelines or manual for RWH systems that is compatible with widely used urban land-use occupancies for greater Dhaka and other urban areas so that the land-use and rainwater management compliance contribute towards achieving sustainability and making sustainable cities. However, enforcement of rainwater management compliance is essential to realize the sustainability of urban water management.

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References

[1]. IPCC 2022, *Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, 2022

[2]. R.A.G. Lezcano, E.J.L.Fernández, D.B. Moyano, and G.S. Contreras, Sustainability in the Urban Water Cycle in Sustainable Cities, *Contemporary Engineering Sciences, 14*, 2021, 23-34. doi:10.12988/ces.2021.91637.

[3]. UN (United Nations), *UN-Water 2020: United Nations World Water Development Report 2020: Water and Climate Change*, Paris, UNESCO, 2020.

[4]. Demographia, World Urban Areas, *Built-Up Urban Areas or Urban Agglomerations'*, 17thAnnual Edition, 2021

[5]. UN-HABITAT, *World Cities Report 2020-The Value of Sustainable Urbanization*, United Nations Human Settlements Programme, 2020.

[6]. K. Shaad, and P., Burlando, Monitoring and modelling of shallow groundwater dynamics in urban context: The case study of Jakarta. *Journal of Hydrology, 573*, 2019, 1046-1056.

[7]. X. Zhang, X. Zhao, and R. Li, Evaluating the vulnerability of physical and virtual water resource networks in China's megacities. *Resources, Conservation and Recycling, 161*, 2020.

[8]. H. Kim, J. Son, S. Lee, S. Koop, K. Van Leeuwen, Y.J. Choi, and J. Park, Assessing Urban Water Management Sustainability of a Megacity: Case Study of Seoul, South Korea, *Water, 10(6)*, 2018, 682.

[9]. E. Li, J. Endter-Wada, and S. Li, Characterizing and contextualizing the water challenges of megacities, *Journal of the American Water Resources Association, 51(3)*, 589-613, 2015.

[10]. A. Chaturvedi, B. Pandey, A.K. Yadav, and S. Saroj, An overview of the potential impacts of global climate change on water resources, *Water Conservation in the Era of Global Climate Change*, 2021. 99-120, Elsevier.

[11]. D. Pavlova, and Y. Milshina, Sustainable water management in megacities of the future,*Urban Ecology*, pp. 201-219,2020, Elsevier.

[12]. D. Li, J. Ma, T. Cheng, J.L. van Genderen, and Z. Shao, Challenges and opportunities for the development of MEGACITIES, *International Journal of Digital Earth*, *12(12*), 2018, 1382-1395.

[13]. UN (United Nations), *World Urbanization Prospects: The 2018 Revision*, New York: Department of Economic and Social Affairs, Population Division, 2018, UN.

[14]. RAJUK (Rajdhani Unnayan Kartripakkha), *Dhaka Structure Plan (2016-2035)*, Regional Development Planning (RDP), Ministry of Housing and Public Works, Government of the People's Republic of Bangladesh, 2015.

[15]. N. Nawar, R. Sorker, F.J. Chowdhury and M.M. Rahman, Present status and historical changes of urban green space in Dhaka city, Bangladesh: A remote sensing driven approach, *Environmental Challenges*, *6*, 2022, 100425.

[16]. Z. Rahman, M. Rama, andA. J. Venables, *Toward Great Dhaka: A New Urban Development Paradigm Eastward Directions in Development*, Washington, DC: World Bank, 2018.

[17]. S. Subrina and F. K. Chowdhury, Urban Dynamics: An undervalued issue for water logging disaster risk management in case of Dhaka city, Bangladesh, *Procedia Engineering*, *212*, 2018, 801-808.

[18]. M.S. Iftekhar, andM.R. Islam, How to transform Dhaka into a water sensitive city,*Urban Water Journal*, 2022.

[19]. DWASA (Dhaka Water Supply and Sewerage Authority), *Annual Report 2020*, Dhaka Water Supply and Sewerage Authority (DWASA), Dhaka, Bangladesh, 2020.

[20]. A. Tabassum, F.H. Ovi, M.A. Hanif, and I. Islam, Rainwater harvesting as an alternative option for sustainable water management of Dhaka city,*WIT Transactions on Ecology and the Environment*, *179*, 2013, 327-337.

[21]. M.M. Islam, M.R. Kabir, and F.N. Chou, Feasibility study of rainwater harvesting techniques in Bangladesh, *Rainwater and Urban Design*,2007, 726-733.

[22]. M.R. Karim, A.B. Shelly, and M. Biswas, People perception and acceptance of rainwater harvesting in a coastal area in Bangladesh, In 12thinternational rainwater catchment systems conference, New Delhi, India, Nov, 2005.

[23]. M.R. Karim, B.S. Sakib, S.S Sakib, and M.A. Imteaz, Rainwater harvesting potentials in commercial buildings in Dhaka: Reliability and economic analysis, *Hydrology*, *8(1)*, 2021, .9.

[24]. A. Palla, I. Gnecco, and P. La Barbera. The impact of domestic rainwater harvesting systems in storm water runoff mitigation at the urban block scale. *Journal of Environmental Management*, *191*, 2017, 297-305.

[25]. M. Sepehri, H. Malekinezhad, A.R. Ilderomi, A. Talebi, and S.Z. Hosseini, Studying the effect of rain water harvesting from roof surfaces on runoff and household consumption reduction, *Sustainable Cities and Society*, *43*, 2018, 317-324.

[26]. A. Rahman, Recent advances in modelling and implementation of rainwater harvesting systems towards sustainable development, *Water*, *9(12)*, 2017, 959.

[27]. V. Sheikh, Perception of domestic rainwater harvesting by Iranian citizens,*Sustainable Cities and Society*, *60*, 2020, 102278.

[28]. V. Pragadeesh Raja, T. Muthukumar, and A. Kalaivani, Assessment of knowledge and perception of rain water harvesting among rural population of Kancheepuram District, Tamil Nadu, *International Journal of Community Medicine and Public Health*, *8(5)*, 2021, 2486..

[29]. Campisano et al., Urban rainwater harvesting systems: Research, implementation and future perspectives", *Water research*, *115*, 2017, 195-209..

[30]. T.B. Mwamila, M.Y. Han, and Z. Katambara, Strategy to overcome barriers of rainwater harvesting, Case study Tanzania, *Journal of Geoscience and Environment Protection*, *4(9)*, 2016, 13-23..

[31]. M. Ahmed, R. Anwar, and M.A. Hossain, Opportunities and limitations in practicing rainwater harvesting systems in Bangladesh. *Int J Civil Eng*, *2(4)*, 2013, 67-74.

[32]. G. Khanal, A. Thapa, N. Devkota, and U.R. Paudel, A review on harvesting and harnessing rainwater: an alternative strategy to cope with drinking water scarcity, *Water Supply*, 20(8), 2020,2951-2963.

[33]. S. Yannopoulos, I. Giannopoulou, and M. Kaiafa-Saropoulou, Investigation of the Current Situation and Prospects for the Development of Rainwater Harvesting as a Tool to Confront Water Scarcity Worldwide, *Water*, *11(10)*, 2019, 2168.

[34]. K. Fahmida, *Feasibility of rooftop rainwater harvesting in Dhaka, Bangladesh*, doctoral diss., The University of Melbourne, Victoria, Australia, 2015.

[35]. M.Z.I. Bashar, M.R. Karim, and M.A. Imteaz, Reliability and economic analysis of urban rainwater harvesting: A comparative study within six major cities of Bangladesh, *Resources*, *Conservation and Recycling*, *133*, 2018, 146-154.

[36]. M.R. Karim, M.Z.I Bashar, and M.A. Imteaz, Reliability and economic analysis of urban rainwater harvesting in a megacity in Bangladesh, *Resources*, *Conservation and Recycling*, *104*, 2015, 61-67.

[37]. K. Wurthmann, Assessing storage requirements, water and energy savings, and costs associated with a residential rainwater harvesting system deployed across two counties in Southeast Florida,*Journal of environmental management*, *252*, 2019, 109673.

[38]. M.M. Islam, F.F. Chou, and M.R. Kabir, Feasibility and acceptability study of rainwater use to the acute water shortage areas in Dhaka City, Bangladesh, *Natural hazards*, *56(1)*, 2011, 93-111.

[39]. GOB (Government of Bangladesh), Dhaka Megacity Building Construction, Improvement, Preservation and Removal Rules, *Bangladesh Gazette*, 29 May 2008, Ministry of Housing and Public Works, Government of the People's Republic of Bangladesh, 2008.

[40]. BNBC (Bangladesh National Building Code),BNBC 2020, *Bangladesh Gazette*, 11 February 2020, Ministry of Housing and Public Works, Government of the People's Republic of Bangladesh, 2020.

[41]. GOB (Government of Bangladesh), Bangladesh Delta Plan 2100, *Baseline Studies on Water Resources Management*, Volume 1, Part A, General Economics Division. Bangladesh Planning Commission, Ministry of Planning, Government of the People's Republic of Bangladesh, 2018.

[42]. JA (Jolshiri Authority), Master plan of Jolshiri Residential Development, Dhaka, Bangladesh, 2015.

[43]. Center for Science and Environment, *A Water Harvesting Manual for Urban Areas Case Studies from Delhi*, Center for Science and Environment, New Delhi, India, 2010.

[44]. A.N. Nithila, P. Shome, and I. Islam, Water logging induced loss and damage assessment of urban households in the monsoon period: a case study of Dhaka, Bangladesh, *Natural Hazards*, *110(3)*, 2022, 1565-1597.

[45]. A. Pacey, and A. Cullis, Rain water Harvesting: The collection of rainfall and runoff in rural areas, *Intermediate Technology Publications*, 1989, London, 55.

[46]. R. Farreny, X. Gabarrell, and J.Rieradevall, Cost-efficiency of rainwater harvesting strategies in dense Mediterranean neighbourhoods, *Resources, Conservation and Recycling*, *55(7)*, 2011, 686–694.

[47]. J. Briggs, and P. Reidy, Advanced water budget analysis for rainwater and related harvesting applications. In World Environmental and Water Resources Congress 2010: Challenges of Change, (pp. 475–484).

American Society of Civil Engineers. In: DeBusk, K., & Hunt, W. (2014). *Rainwater Harvesting: A Comprehensive Review of Literature Report*,*425*, 2010, 164, Water Resources Research Institute of The University of North Carolina.

[48]. M. A. Imteaz, O. B. Adeboye, S. Rayburg, and Shanableh, A. Rainwater harvesting potential for southwest Nigeria using daily water balance model, *Resources, Conservation and Recycling*, *62*, 2012, 51–55.

[49]. M. A. Imteaz, A. Ahsan, J. Naser, and A. Rahman, Reliability analysis of rainwater tanks in Melbourne using daily water balance model, *Resources, Conservation and Recycling,*56(1), 2011, 80–86.

[50]. B. Ebenezer, and J.J. Nsiah, Quantifying Rooftop Rainwater Harvest Potential: Case of Takoradi Polytechnic in Takoradi, Ghana, *International Journal of Science and Research (IJSR),5*, 6-391, 2015.

[51]. O.O. Aladenola, and O.B. Adeboye, Assessing the potential for rainwater harvesting, *Water resources management*, *24(10)*, 2010, 2129-2137.