



Feasibility of rainwater harvesting for sustainable water management in urban areas of Egypt

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Abstract

Egypt's limited water resources, rapid population growth, and climate change are increasing the gap between water demand and supply. Meanwhile, significant amounts of rain fall in some regions in Egypt during specific storm events, which in some cases, lead to disasters like flash floods and inundations. Rainwater harvesting (RWH) can be considered as a sustainable promising solution to water shortage and inundation problems. In this work, the feasibility of RWH for urban areas was assessed over 22 cities throughout Egypt. Results show that the annual volume of rainwater harvested can reach 142.5 MCM in the considered cities, provided that all rain falling on the urban areas is collected. High potential of rainfall harvesting was found for cities that located on the North Coast, e.g., the potential water saving from the share of RWH in Alexandria can satisfy around 12% of its future supplementary domestic water needs. In contrast, rainfall over the cities located on the middle and the south of the country is insignificant to be harvested. A case study for the 5th settlement region in Cairo was discussed in terms of groundwater recharge and surface runoff estimation for two conditions: No-RWH and RWH systems by implementing recharge wells to store rainwater into the aquifer. Land cover classification maps of urban areas were created by using the ARCGIS software to estimate equivalent infiltration coefficients. The results demonstrate that the implementation of such RWH system has a significant impact on the regional water cycle, where the effective infiltration coefficient increased from 10% (No-RWH) to 75% (RWH) in the case study. Accordingly, the runoff coefficient decreased in the case study from 0.8 (No-RWH) to 0.15 (RWH), and the volume of runoff decreased in the case of RWH by around 82% lower than that of the No-RWH condition. Thus, direct infiltration of RWH into an aquifer can play an important role in sound water management for urban environments, as this may lead to a significant reduction in risks of flooding and expenses of municipal drainage systems installation and operation.

Keywords Rainfall · Rainwater harvesting · Groundwater recharge · Water management · Infiltration coefficient · Water savings · Egypt

Introduction

Scientists warned that the gap between demand and supply in many countries could exceed 40 percent due to threats of

climate change and population growth within 20 years (Daily Mail 2011). Particularly in Egypt, renewable water resources are considered limited and rely mainly on the Nile River (55.5 BCM/year) (billion cubic meter per year) that represents 97%. Meanwhile, Egypt population are growing rapidly (2% annually) (World Bank 2017), causing stress on water resources due to increased water requirements for domestic consumption and increased use of irrigation water to meet higher food demands. In year 2015, the population reached 90 million while water availability was 611 m³/capita/year; and the population is expected to reach 140 million by the year 2037 and water availability will be 392 m³/capita/year (MWRI 2015). Therefore, developing water conservation techniques and controlling water pollution have become necessary to meet current challenges facing scientists, engineers, and policy makers as the comprehensive

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development of the country in the different fields depends on the availability of such vital resource. In addition, rainwater harvesting and desalination of both saline and brackish water are currently available alternatives for increasing water resources in Egypt.

Various urban regions are exposed to significant amounts of rainfall during specific storm events, which in some cases, may lead to flash floods and inundations problems. In this regard, rainwater harvesting (RWH) can be considered a sustainable adaptation measure that could overcome both water scarcity and inundation problems in urban areas. RWH can be defined as a technique for collecting and storing rainwater from specific catchments such as rooftops and land surfaces, by using simple equipment (e.g., pots and tanks) or quite complex techniques (e.g., underground tanks and check dams) (Abdulla and Al-Shareef 2009). RWH provides a renewable

source of clean water which is perfect for several uses. For domestic water use, several studies concluded that RWH can save substantial water in various countries such as Germany (Hermann and Schmida 1999), Australia (Coombes et al. 2000), Brazil (Ghisi et al. 2006), Jordan (Abdulla and Al-Shareef 2009), and Portugal (Lúcio et al. 2019). Recently, some studies addressed the perceived risks associated with stormwater quality when used for different applications (e.g., Lundy et al. 2018).

One of the major concerns in urban hydrology is the reduction of rainfall infiltration that leads to diminution of groundwater recharge, increase the risk of flooding, and accelerate the transport of pollutants. Thus, recently, some studies were conducted to improve the performance of the integrated urban water systems such as Behzadian et al. (2018). This study assessed the potential of using smart RWH schemes to

Table 1 Summary of recent studies on extreme rainfall events in Egypt

Study	Region	No. of stations	Observation period	Rainfall duration	Distribution/model	Main findings
Soliman (1953)	Egypt	30	Up to 1945	1 day		Winter is the season of rain in the north of Egypt, but in the south (Upper Egypt), May and October are found to be the two rainy seasons.
El-Shafie et al. (2011)	Alexandria	1	1957–2009	1 day	ANN and MLR	The performance of the ANN model is better than that of the MLR.
El-Sayed (2011)	Sinai	12	1990–2010	5, 15, 30, 60 min and 2, 24 h	Gumbel, GEV, Normal, Log-normal, Weibull, Pearson III, Log-Pearson III	A regional IDF formula was proposed for Sinai.
Said et al. (2012)	Alexandria	1	1979–2011	1 day		Three extreme events were observed in the study area.
El-Afandi et al. (2013)	Sinai	6	January 17 to 19, 2010	1 h	Weather Research and Forecasting (WRF)	The WRF model was able to capture the heavy rainfall events over Sinai.
Ibrahim and El-Afandi (2014)	Egypt	5	December 10, 2013	1 day	WRF	The WRF model demonstrated a good ability to predict the heavy rainfall events over Egypt.
Fathy et al. (2014)	Sinai	5	1990–2010		California, Hazen, Kimball and Gumbel	New IDF curves of Sinai were constructed.
Yehia et al. (2017)	Alexandria region and Upper Egypt		1980–2015	1 day	Linear regression	A proposed plan was suggested to eliminate the impact of extreme rainfalls on water resources quality and water supplies.
Gado (2017)	Egypt	30	1904–2015	1 day	GEV	A great variation in all different aspects of rainfall was shown over Egypt.
Salama et al. (2018)	Egypt	30	1904–2017	1 day	N, LN, PIII, LPIII, Gumbel, GEV	The Log-Normal and Log-Pearson Type III distributions are the best models for describing the distribution of daily annual maximum rainfalls in Egypt.
Gado et al. (2019)	Egypt	31	1904–2016	1 day	Mann-Kendall, Spearman, Pearson	About 29% of the analyzed stations exhibited significant trends, most of them were decreasing trends.

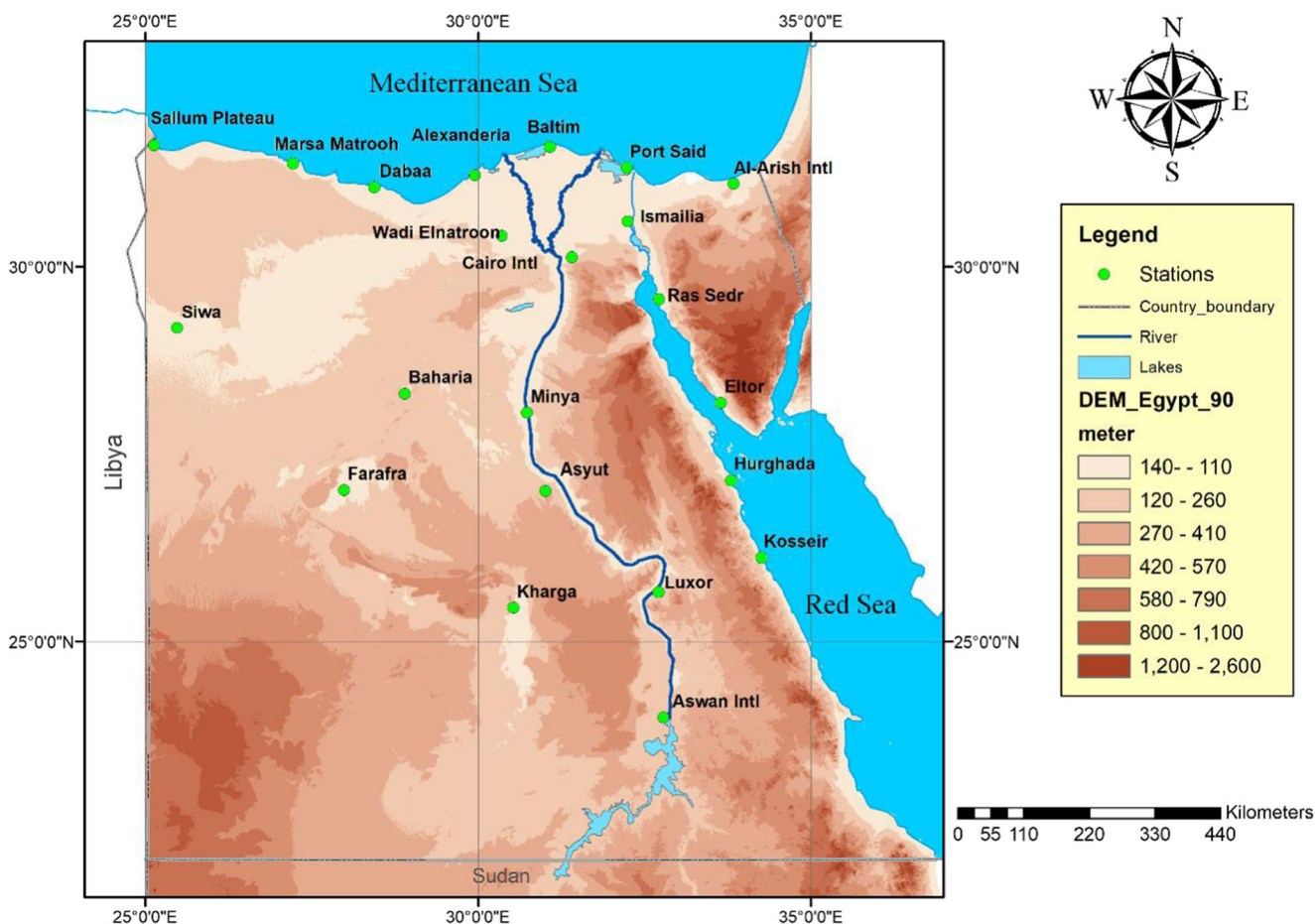


Fig. 1 Map of the selected rainfall stations in Egypt

mitigate local floods and supply harvested rainwater to non-potable water consumption. Directing rainwater to recharge local aquifers through infiltration wells has become a new technique of RWH (e.g., Dillon 2005; Nachshona et al. 2016). This new RWH system, which includes execution of recharge wells, is favored in urban environments because of the limitation of (1) surface areas that allow rainwater to infiltrate to groundwater; and (2) free spaces that can be used to locate storing tanks. Implementation of such RWH system increases groundwater recharge and decreases surface runoff volumes (Nachshona et al. 2016).

Flash floods in Egypt were investigated in some recent studies. For example, an early warning system for flash floods was developed for Wadi Watir in the Sinai Peninsula (Cools et al. 2012). They stated that 20 significant rain events were measured over a period of 30 years (1979–2010), nine of them resulted in flash floods. Thus, the water harvesting potential was evaluated in Wadi Watier in some research such as Al-Zayed et al. (2013). Wadi El Arish in Sinai was subjected to severe thunderstorms on January 17 and 18, 2010, followed by the extreme violent flood that claimed six victims, tens of injured, and devastated vital infrastructure and hundreds of houses (Moawad

2013). This flash flood was analyzed, based on the integration of remote sensing and GIS, to monitor the general development of the storm rain and to estimate the surface runoff (Moawad 2013). Using the Weather Research and Forecasting (WRF) model, El-Afandi et al. (2013) investigated heavy rainfall events that occurred over Sinai. The performance of the WRF model was also evaluated in heavy rainfall prediction over Egypt (Ibrahim and El-Afandi 2014). Moawad et al. (2016) estimated the surface runoff of the flash flood that occurred in Qena, on January 28, 2013. Recently, some studies have investigated characteristics of precipitation in Egypt as summarized in Table 1.

The limited water resources in Egypt along with the severe damage caused by several flash floods point to the necessity to study the potential of RWH for urban areas in Egypt. Nevertheless, scanning the literature reveals that little has been done regarding investigating RWH in Egypt. Thus, in this paper, the capability of RWH was evaluated over 22 cities throughout Egypt in order to cope with water scarcity and inundation problems in urban environments. Moreover, the potential impact of RWH that includes implementation of recharge wells on the regional hydrological cycle was discussed on a case study in Cairo, Egypt.

Study area and data

Egypt lies between latitudes 22° and 32° N, and longitudes 25° and 35° E and it has an area of 1,001,450 km². Figure 1 shows the topography map of Egypt created by using the Shuttle Radar Topography Mission (SRTM) 90-m digital elevation model (Jarvis et al. 2008). The land elevation varies from 133 m below the mean sea level at the Qattara Depression to 2629 m above the mean sea level at the Mount Catherine (Nashwan et al. 2018). Aside from the Nile Valley and few scattered oases, most of Egypt’s landscape is desert. Egypt has four seasons: winter, spring, summer, and autumn. In general, the winter is cold, moist, and rainy but summer is hot, dry, and rainless. The spring and the autumn are transitional seasons. The annual average of daily maximum and minimum temperature ranges from 22.3 to 35.0 °C and 10.0 to 22.5 °C, respectively over the country (Nashwan et al. 2018). Rainfall over Egypt is concentrated in the north coast which decreases rapidly inland to Middle Egypt becoming too rare in Upper Egypt and western dessert (Gado 2017). The common origin of most rain events in Egypt is that they are local, convective events with a high spatial variability and short duration. In autumn and winter, some cases of heavy rainfall may cause flash flood mainly over the Red Sea Mountains and the Sinai Peninsula (Ibrahim and El-Afandi 2014).

In this study, the database consists of 22 stations throughout Egypt (Fig. 1). The database was taken from a previous study (Gado 2017) in which data were compiled from multiple sources and checked for consistency over the periods of overlap to get long record over the available stations. The selection of the stations is made in such a way that the observed series are stationary in the mean. Furthermore, the rainfall data was verified to be independent and homogeneous; and very few outliers were detected and removed from the database. Some of the characteristics of the selected stations are shown in Table 2, where the period of record and the record length for each station are also listed. The rainfall record length varies from a minimum of 15 years at Kharga station to a maximum of 55 years at Alexandria Intl station, with an average of 28 years. Two types of monthly and annual rainfall data were considered: total rainfall and total number of rainy days.

Statistical characteristics of rainfall data in Egypt

Here, the statistical characteristics of rainfall data in Egypt were investigated in order to study the potentiality of rainfall harvesting in the country. Inverse distance

Table 2 Summary of the characteristics of the studied stations (Modified after Gado 2017)

Station ID	Station name	Latitude	Longitude	Elevation (m)	Period of record	Record length (years)
62337	Al-Arish Intl	31.07	33.84	36.9	1985–2017	33
62318	Alexandria Intl	31.18	29.95	1.8	1957–2017	55
62414	Aswan Intl	23.97	32.78	200	1962–2017	22
62393	Asyut	27.04	31.01	226	1960–2014	20
62420	Baharia	28.33	28.90	130	1957–2017	27
62325	Baltim	31.55	31.08	2	1994–2017	24
62366	Cairo Intl	30.12	31.41	75	1957–2017	53
62309	Dabaa	31.03	28.44	18	1963–2017	23
62459	Eltor	28.21	33.65	35	1961–2015	22
62423	Farafra	27.05	27.98	92	1957–2016	17
62463	Hurghada	27.18	33.80	14	1991–2017	18
62440	Ismailia	30.59	32.25	13	1987–2013	26
62435	Kharga	25.46	30.53	73	1961–2014	15
62465	Kosseir	26.14	34.26	11	1960–2014	26
62405	Luxor	25.67	32.71	99	1957–2016	33
62306	Marsa Matrooh	31.33	27.22	30	1957–2017	51
62387	Minya	28.08	30.73	37	1957–2016	32
62332	Port Said	31.28	32.24	6	1987–2014	28
62455	Elgamil Ras Sedr	29.58	32.72	16	2000–2017	18
62305	Salloum Plateau	31.57	25.13	6	1996–2017	21
62417	Siwa	29.20	25.48	– 12	1957–2017	37
62357	Wadi Elnatroon	30.40	30.36	1	1996–2017	19

weighting method (IDW) was used to interpolate rainfall data of the available stations to produce continued raster surfaces for Egypt boundary. IDW interpolation is defined as a spatially weighted average of the sample values within a search neighborhood (Shepard 1968). It is one of the simplest and most popular interpolation techniques for natural phenomenon (Babak and Deutsch 2009). Two types of non-zero precipitation data were considered as mentioned earlier: total rainfall and number of rainy days.

Total rainfall

The average monthly and annual rainfall in the studied stations in Egypt are shown in Table 3. Figure 2 shows the spatial variation of the average annual total precipitation over the country. It can easily be noticed high variations of the average values of both annual and monthly precipitation among not only the studied stations but also over the different months (Table 3). Specifically, the overall average annual rainfall for all stations is 52.5 mm, which ranges from 9 to 172 mm. It exceeded 100 mm at four stations located on the North Coast (Fig. 2): Alexandria Intl (172 mm), Baltim (140 mm), Marsa Matrooh (122 mm), and Dabaa (112 mm). Hence, there is a significant amount of rainwater that can be harvested in these cities. On the

other hand, the average annual total precipitation did not exceed 10 mm at three stations located on the middle and the south of the country (Fig. 2): Aswan Intl (9 mm), Siwa (10 mm), and Ras Sedr (10 mm). Figure 3 displays the annual rainfall of Cairo Intl station for the period 1957–2017, where it varied between a minimum amount of 1 mm in 1959 and a maximum of 197 mm in 2016.

Number of rainy days

The average monthly and annual number of rainy days in the studied stations in Egypt are shown in Table 4. Figure 4 shows the spatial variation of the average annual number of rainy days over the country, where it ranges from 1 to 33 days. It exceeded 20 days at six stations located on the North Coast (Fig. 4): Alexandria Intl (33 days), Baltim (31 days), Dabaa (30 days), Marsa Matrooh (28 days), Port Said Elgamil (23 days), and Al-Arish Intl (20 days). In contrast, it can be shown that the mean annual number of rainy days did not exceed 3 days at 11 stations located on the middle and the south of the country (Fig. 4): Farafra, Aswan Intl, Asyut, Baharia, Hurghada, Kharga, Kosseir, Luxor, Eltor, Minya, and Siwa. The mean monthly number of rainy days ranged from zero at some stations in different months to nine days at Alexandria and Baltim in January

Table 3 Average monthly and annual rainfall (mm) in the studied stations in Egypt

Month	1	2	3	4	5	6	7	8	9	10	11	12	Annual
City													
Al-Arish Intl	23	16	20	8	10	2	3	25	0	9	8	19	87
Alexandria Intl	47	30	16	6	4	4	15	17	7	16	30	46	172
Aswan Intl	3	1	8	24	2	27	6	2	5	2	1	1	9
Asyut	2	13	9	52	5	27	38	11	0	115	8	29	39
Baharia	1	4	4	2	1	0	7	8	59	4	27	22	18
Baltim	40	37	14	5	4	0	4	0	26	14	13	34	140
Cairo Intl	7	7	12	4	6	5	6	27	20	11	11	12	42
Dabaa	34	15	10	4	8	0	3	0	5	21	16	25	112
Eltor	3	1	9	5	3	0	4	0	70	2	7	13	16
Farafra	3	5	1	32	1	0	13	0	0	11	16	4	12
Hurghada	8	1	34	1	43	3	5	34	70	30	32	54	45
Ismailia	14	9	9	12	2	0	10	0	51	9	3	6	45
Kharga	12	1	3	16	15	30	4	0	4	0	4	30	14
Kosseir	5	11	2	6	9	2	12	73	20	6	3	3	21
Luxor	7	1	10	20	14	15	24	8	6	4	13	63	22
Marsa Matrooh	32	21	11	9	9	20	4	0	5	18	19	34	122
Minya	2	6	2	51	4	0	5	20	72	19	18	16	18
Port Said Elgamil	35	17	9	11	15	6	1	50	29	12	16	9	99
Ras Sedr	4	4	2	15	8	0	2	0	0	3	2	3	10
Salloum Plateau	15	12	6	5	11	17	3	2	18	18	6	14	61
Siwa	3	3	2	3	4	3	8	102	2	9	2	4	10
Wadi Elnatroon	8	12	3	11	4	0	17	0	0	7	10	13	40

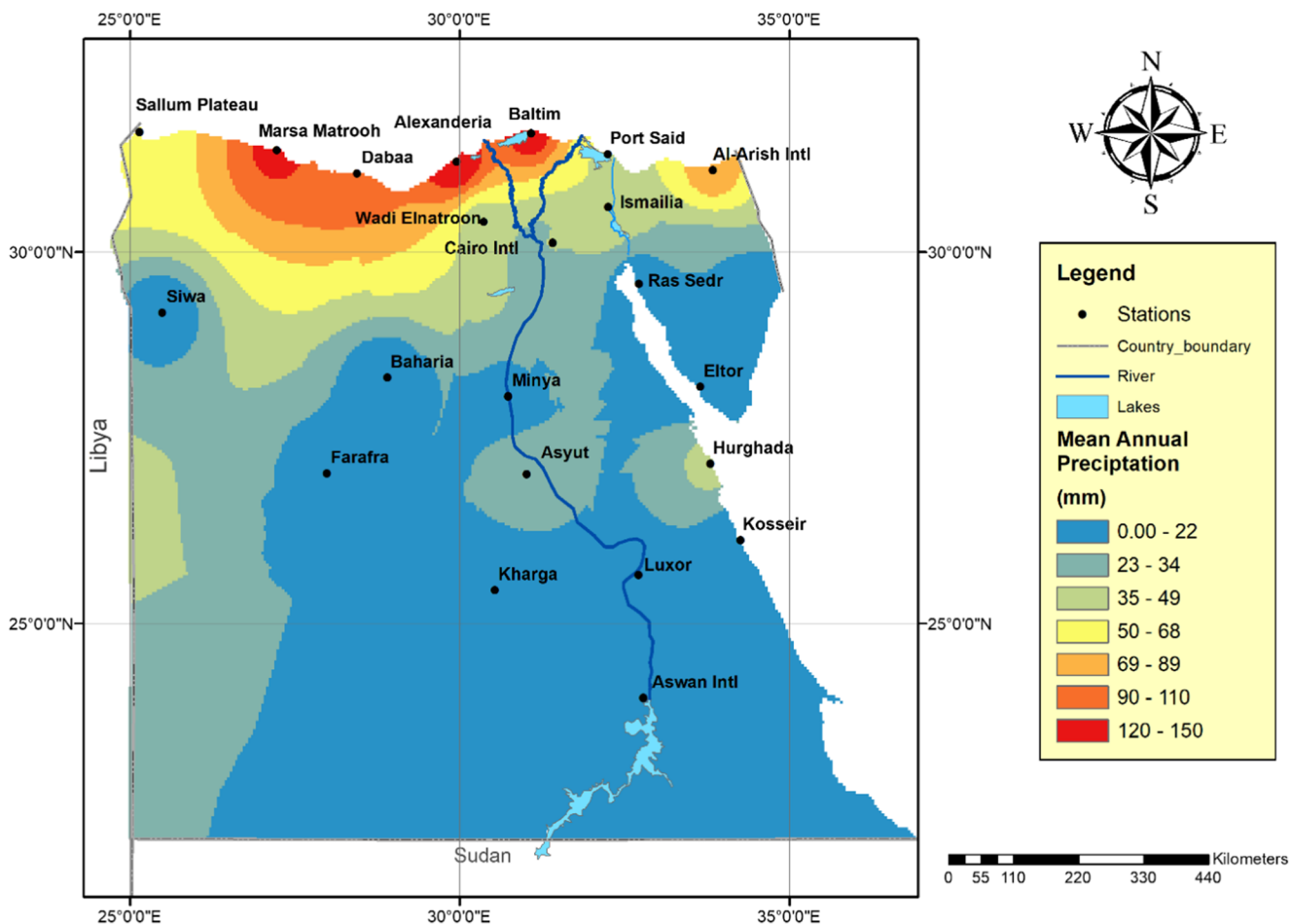


Fig. 2 Spatial distribution of mean annual precipitation in Egypt

(Table 4). It can be concluded that the rainy season in Egypt extends from October to March, with the peak of precipitation taking place during December, January, and February. Figure 5 displays the annual number of rainy days at Cairo Intl station for the period 1957–2017, where it varied between a minimum of one day in 1959 and 1978 and a maximum of 30 days in 1994.

Rainwater harvesting prospects for Egyptian cities

Rainwater harvesting can increase water supply in Egypt for various uses and help reduce the growing supply-demand gap. However, RWH from urban catchments has not received enough attention yet. In this paper, the annual volume of

Fig. 3 Total annual precipitation of Cairo Intl station for the period 1957–2017

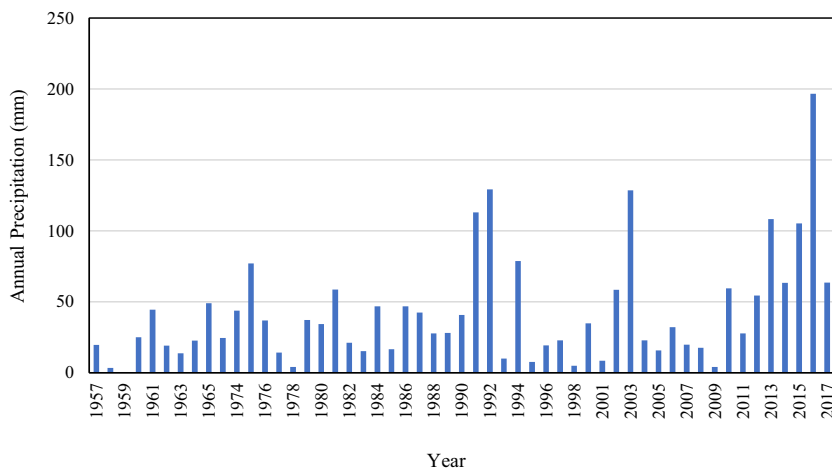


Table 4 Average monthly and annual rainy days (day) of the studied stations in Egypt

Month	1	2	3	4	5	6	7	8	9	10	11	12	Annual
City													
Al-Arish	6	5	4	2	1	1	2	1	0	2	2	4	20
Alexandria	9	7	4	2	1	1	2	1	1	3	5	7	33
Aswan	1	1	1	1	1	1	2	1	2	2	1	1	2
Asyut	1	1	1	2	1	1	2	1	0	2	1	2	2
Baharia	1	2	1	1	1	0	2	1	1	1	1	1	2
Baltim	9	8	4	2	2	0	2	0	1	3	4	7	31
Cairo Intl	3	3	2	2	1	1	2	1	2	1	2	3	10
Dabaa	8	5	3	2	2	0	2	0	2	3	4	6	30
Eltor	2	1	2	1	2	0	2	0	1	1	1	2	3
Farafra	1	1	1	1	1	0	2	0	0	1	2	2	1
Hurghada	1	1	1	1	1	1	2	1	1	2	2	1	2
Ismailia	4	3	2	2	2	0	2	0	1	2	2	3	12
Kharga	1	1	2	1	1	1	2	0	1	0	1	1	2
Kosseir	1	1	1	1	1	1	1	1	1	1	1	2	2
Luxor	1	1	2	2	1	1	2	1	1	2	1	1	2
Marsa Matrooh	7	7	4	2	2	1	1	0	2	3	4	6	28
Minya	1	1	1	2	1	0	1	1	1	2	1	1	3
Port Said Elgamil	6	5	4	2	2	1	1	1	1	3	3	4	23
Ras Sedr	2	2	1	1	2	0	1	0	0	2	1	2	6
Salloum Plateau	4	4	2	1	1	1	2	1	2	3	2	3	15
Siwa	2	1	1	2	2	1	2	1	1	2	1	2	3
Wadi Elnatroon	3	2	1	1	2	0	1	0	0	1	1	2	8

rainwater (AVR) that could be harvested in each city was estimated considering the average annual rainfall (AR), the total urban area (A), and a runoff coefficient (C) as follows:

$$AVR = (AR \times A \times C / 1000) \quad (1)$$

where the dimensions of AVR, AR, A , and C are the following: m^3 /year, mm/year, m^2 , and non-dimensional, respectively. Here, the runoff coefficient (C) is assumed to be 0.8, which indicates a loss of 20% of rainwater that may be wasted due to evaporation and infiltration (Abdulla and Al-Shareef 2009). To estimate urban areas (i.e., buildings and asphalt) in the 22 cities, land-use maps were created by using manual digitizing of high-resolution satellite images, which is processed in the ARCGIS software.

The annual volume of rainwater that could be harvested in each of the 22 cities was shown in Table 5. A maximum of 142.5 MCM (million cubic meter) of rainwater can be annually harvested from the studied cities provided that all rain falling on the urban areas is collected. The potential of annual water harvesting varies among the cities from 0.02 MCM at Farafra to 60.32 MCM at Cairo (Table 5). It is worth mentioning here that although the average annual precipitation in

Cairo is around 42 mm (Table 5), extreme rainfall events that may occur every 10 years are about 43 mm/day (Gado 2017). Considering the urban area of Cairo is approximately $1.8 \times 10^9 m^2$ (Table 5), the volume of harvested rainwater in a 1 day of such extreme storm could be in the order of 77 MCM.

The current master plan for water and sanitation of Egypt up to 2037 was established by the Holding Company for Water and Wastewater (HCWW), which consists of 25 affiliated companies, provides drinking water and wastewater disposal services for the 27 governorates of Egypt (HCWW 2015). The company prioritizes a number of potential water projects in order to increase the annual volume of domestic water supply for 19 cities from 7 BCM (billion cubic meter) produced in year 2015 to 11.4 BCM in 2037 (unpublished data from HCWW). Considering the present situation of water shortage facing the water sector in Egypt, satisfying these amounts of water through the irrigation network has become a major challenge particularly at plants located at the tail end of the irrigation system or far away from it. Therefore, attention to non-conventional water resources like rainwater harvesting is gaining importance.

The volume of RWH from the available cities in the region of each company was calculated and compared with the required increased volume of water supply of the company, in order to estimate the share of RWH of its future supplementary needs of domestic water (Table 6). The results show that the potential water savings ranged from 0% at three companies located in Upper Egypt to 12% at Alexandria located at the North Coast (Table 6). It can be concluded that the urban RWH of Alexandria city can satisfy 12% of the future additional domestic water needs of Alexandria company. For Marsa Matrooh company, 7% of their future extra domestic water needs can be fulfilled by the urban RWH in four cities: Marsa Matrooh, Dabaa, Salloum, and Siwa. In Sinai, the RWH of one and only city (Al-Arish) in the north and only two cities in the south (Eltor and Ras Sedr) can provide 7% and 8% of the future additional domestic water needs of both North and South Sinai companies, respectively. The RWH of both Port Said and Ismailia can provide 4% of the required increased domestic water in the canal cities company. The RWH of Cairo can satisfy 3% of the required increased domestic water in both Cairo and Giza companies. In contrast, the potential for water saving in the middle and south of the country is marginal due to insignificant amounts of annual rainfall on these regions (Table 6).

A case study of RWH (The 5th settlement region, Cairo)

The 5th settlement region, which is a part of the greater Cairo and located east of the River Nile (Fig. 6), was

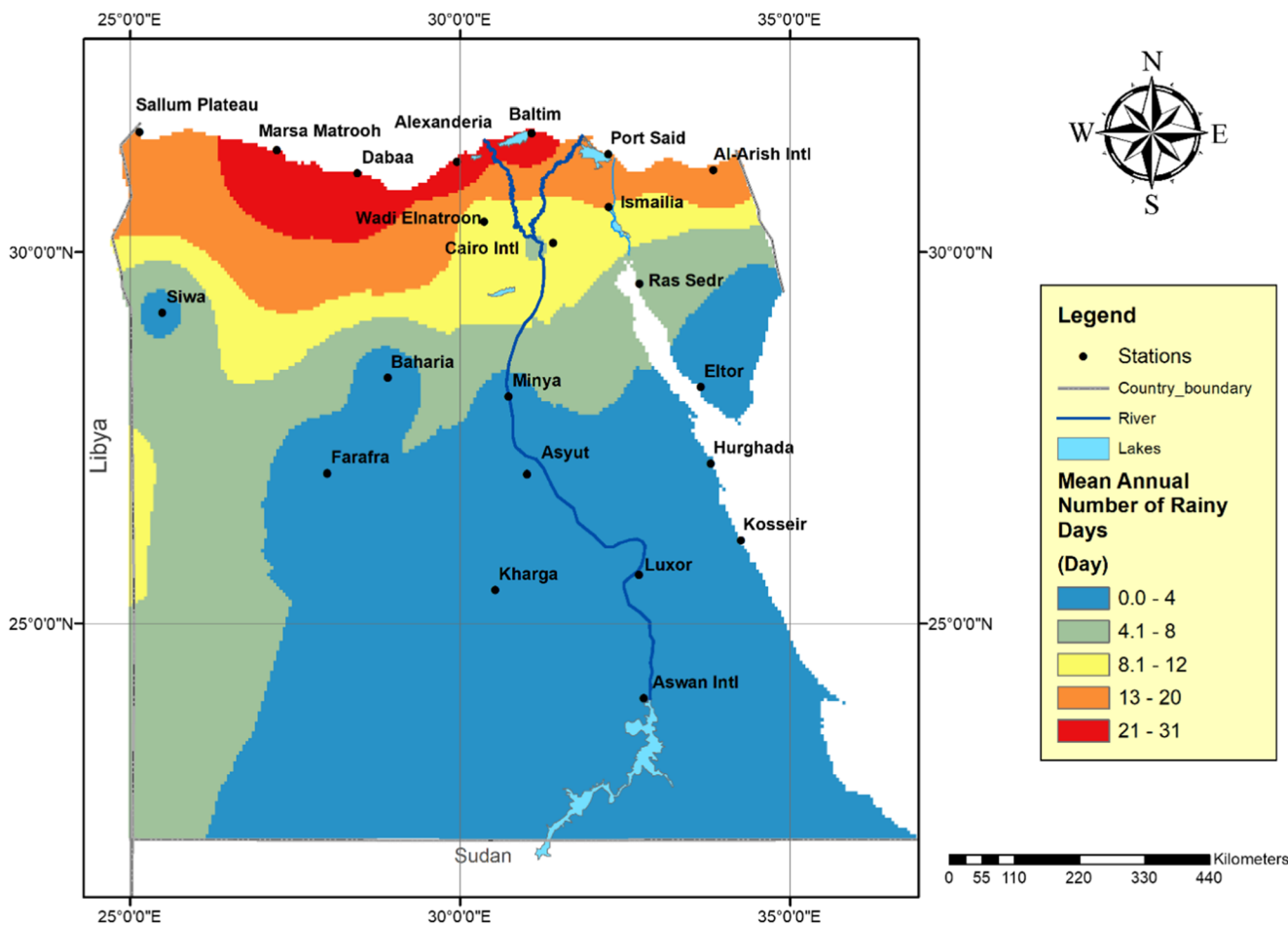


Fig. 4 Spatial distribution of mean annual number of rainy days in Egypt

selected to study groundwater recharge and surface runoff estimation for two conditions: No-RWH and RWH system by implementing recharge wells. Its surface area is about 12000 km², where the land topography slopes from South-East to North-West, as shown in Fig. 6. The climate of the region is arid with very hot summer and mild winter. The 5th settlement region overlies the Fissured Carbonate aquifer which extends in 50% of Egypt area covering an area of 500,000 km² (Abdel-Shafy and

Kamel 2016), as shown in Fig. 7. The geological age of the aquifer belongs to Oligocene period and it is 250-m thickness and consists of fluvialite and fluviomarine sandy series capped by basalt rocks (CONOCO 1987; El-Sayed 2018). This aquifer is hydraulically connected with Quaternary aquifer running under the Nile through fault planes (El-Sayed 2018). The hydraulic conductivity of the Fissured Carbonate aquifer ranges between 6.4×10^{-5} and 2.1×10^{-3} m/s (Wagdy et al. 2008).

Fig. 5 Annual number of rainy days of Cairo Intl station for the period 1957–2017

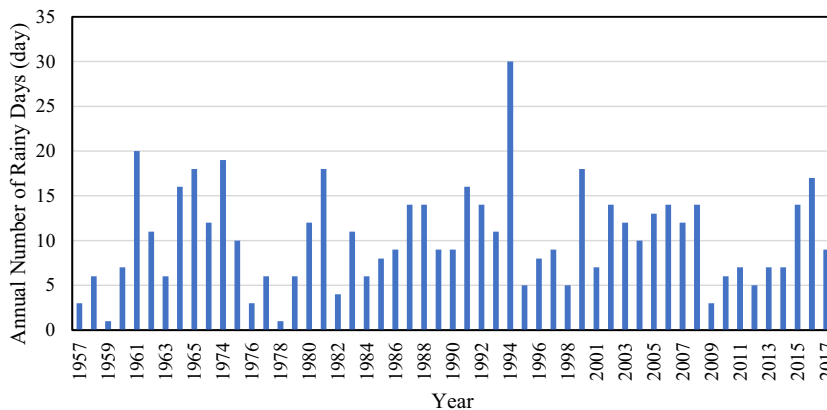


Table 5 Volume of harvested rainfall in the selected cities in Egypt

City	Urban area (m ²)	Average rainfall (mm/year)	Average harvested rainfall (MCM/year)
Al-Arish	39,884,373	87	2.769571
Alexandria	432,854,534	172	59.560784
Aswan	28,321,970	9	0.197121
Asyut	39,427,161	39	1.220665
Baharia	7,313,058	18	0.107648
Baltim	6,463,888	140	0.723438
Cairo	1,799,592,976	42	60.322357
Dabaa	14,530,085	112	1.305383
Eltor	13,966,750	16	0.182126
Farafra	2,214,672	12	0.021792
Hurghada	50,975,970	45	1.835135
Ismailia	85,871,907	45	3.105128
Kharga	12,868,675	14	0.140011
Kosseir	8,620,559	21	0.146894
Luxor	22,400,189	22	0.385283
Marsa Matrooh	65,108,998	122	6.339012
Minya	17,443,597	18	0.256770
Port Said	40,517,193	99	3.208962
Ras Sedr	3,961,070	10	0.031372
Salloum	4,857,942	61	0.236290
Siwa	5,384,189	10	0.042212
Wadi Elnatroon	12,288,691	40	0.388323
Total			142.526277

Groundwater recharge

Infiltration coefficients are commonly used to estimate the fraction of rainwater that goes underground to the vadose zone or the aquifer. They depend on soil hydraulic properties, topography, vegetation, and land use (Pauleit and Duhme 2000). In the case of a given area that has different land cover components, an effective infiltration coefficient $I_{c(\text{eff})}$ can be estimated as follows (Nachshona et al. 2016):

$$I_{c(\text{eff})} = \frac{\sum A_{(i)} \times I_{c(i)}}{\sum A_{(i)}} \quad (2)$$

where $I_{c(i)}$ and $A_{(i)}$ are the infiltration coefficient and the surface area of a component (i), respectively. Annual volume of infiltrated water into groundwater (AVI) can be calculated by Eq. (1), with replacing $I_{c(\text{eff})}$ in place of the runoff coefficient (C).

In urban environments, four major land cover components can be distinguished: buildings, asphalt areas, parks, and bare soil. Here, the land-use map of the study area was produced by the ARCGIS software for digitizing the area of each component using high resolution Google earth images (Fig. 6). By knowing the surface areas and the infiltration coefficients of

the major components of the study area, it is possible to calculate its effective infiltration coefficient ($I_{c(\text{eff})}$) by Eq. (2). Infiltration coefficients (I_c) of buildings, asphalt areas, parks, and bare soil are assumed to be 5%, 5%, 35%, and 50%, respectively (Nachshona et al. 2016). In this study, it is assumed that 80% of the rainwater infiltrates to the subsurface in the case of RWH system that implements recharge wells (Nachshona et al. 2016). Thus, in this case, I_c for both buildings and asphalt areas will be taken as 80% (Table 7).

The spatial fraction of each land cover is presented in Table 7 along with the calculated $I_{c(\text{eff})}$ and the volume of groundwater recharge for both RWH and No-RWH conditions, considering the average annual precipitation at the region (AR) equal to 42 mm/year (Table 5). The implementation of RWH system in the region has a significant impact on the regional water cycle as demonstrated in Table 7. The calculated values of $I_{c(\text{eff})}$ for the region are 10% and 75% for No-RWH and RWH conditions, respectively. Consequently, the implementation of RWH system can increase the effective infiltration coefficient by a factor of 7.5 for the region in compare to the No-RWH condition. In view of the total surface area and the average annual rainfall of the region, the average annual infiltration may increase from 0.05 to 0.38 MCM by implementing the RWH system over the region (Table 7).

Table 6 The share of RWH to satisfy the required increased volume of water supply of the HCWW from 2015 to 2037

Municipal Water Company	City	Capacity of municipal company at 2015 (MCM/year)	Rainwater harvesting (MCM/year)	Required increase of water supply from 2015 to 2037 (MCM/year)	RWH satisfy future needs (%)
Cairo + Giza	Cairo	4042.375	60.32	2333.81	3
Alexandria	Alexandria	1085.875	59.56	500.78	12
Marsa Matrooh	Marsa Matrooh + Dabaa + Salloum + Siwa	80.3	7.92	116.44	7
Aswan	Aswan	122.64	0.37	59.86	1
Minya	Minya	355.51	0.26	663.94	0
Luxor	Luxor	98.55	0.39	85.12	0
Asyut	Asyut	231.045	1.22	524.51	0
New Vally	Kharga + Farafra	58.765	0.16	21.90	1
Red Sea	Kosseir + Hurghada	44.53	1.98	169.36	1
Qanal Cities	Port Said + Ismailia	485.085	6.31	174.11	4
North Sanai	Al-Arish	80.3	2.77	41.98	7
South Sinai	Eltor + Ras Sedr	33.945	0.21	2.56	8

Thus, the implementation of such RWH may increase the groundwater recharge in the case study by around 650% higher than that of the No–RWH condition. As a result, this will lead to a significant reduction in surface runoff (see the “Surface runoff estimation” section) and flood risks.

Surface runoff estimation

The topography of the study area was investigated by using the Shuttle Radar Topography Mission Digital Elevation Model (ASTER GDEM 2011) with 30-m resolution. The studied area has elevations above sea level varies from 341 m at the South-East to 244 m at the North-West, as shown in Fig. 6. The natural drainage direction for every pixel was determined to produce the flow direction map (Jenson and Domingue 1988). Accordingly, the flow accumulation map was derived which counts the total number of pixels that will drain into outlets as shown in Fig. 8. Additionally, according to Tarboton et al. (1991), the drainage pattern of the study area was deduced, and streamlines were digitized, as shown in Fig. 8.

The results indicated that the maximum value of the accumulated flow in the case study is 410 (dimensionless) at the North-West of the area (Fig. 8). In the case of No–RWH, the runoff coefficient can be estimated to be 0.8, as the effective infiltration coefficient $I_{c(eff)} = 10\%$ (Table 7), and assuming 10% of rainfall could be lost due to evaporation and detention. Thus, it can be concluded that the maximum annual volume of runoff is in the order of 12400 m³ at the 90th street (Fig. 6) (the average annual rainfall is 42 mm at Cairo station and the area of each pixel is 30 × 30 m²). In the same way, for extreme rainfall events with a return period of 10 years (43 mm/day),

the maximum volume of runoff in a 1-day extreme storm could be in the order of 12700 m³. A comparable storm happened on April 24, 2018, when water level raised to exceed one meter in the 90th street (the most affected area by the flash flood) and caused severe damages to infrastructures and cars (Ahran Online 2018).

In the case of RWH, the runoff coefficient can be taken as 0.15 ($I_{c(eff)} = 75\%$ as shown in Table 7). As a result, the maximum annual volume of runoff could be in the order of 2300 m³. Hence, the implementation of RWH may decrease the volume of runoff in the case study by around 82% lower than that of the No–RWH condition. Consequently, this will lead to a significant reduction in the expenses of the municipal drainage system installation and operation in the studied region.

Conclusions

In Egypt, the Holding Company for Water and Wastewater (HCWW) established a master plan to increase the annual volume of domestic water supply from 7 BCM produced in year 2015 to 11.4 BCM in 2037 (HCWW 2015). Yet, satisfying these amounts of water has become a major challenge because of the current critical water shortage in the country. Thus, rainwater harvesting, as a non-conventional water resource, should receive much attention. To study the potential of rainfall harvesting in Egypt, the statistical characteristics of two types of rainfall data, total rainfall and number of rainy days in 22 cities, were investigated. It was found that the studied cities which located on the North Coast have high potential for rainfall harvesting, while rainfall over the cities located on the middle and the south of the country is insignificant to be harvested. Generally, the rainy season in Egypt

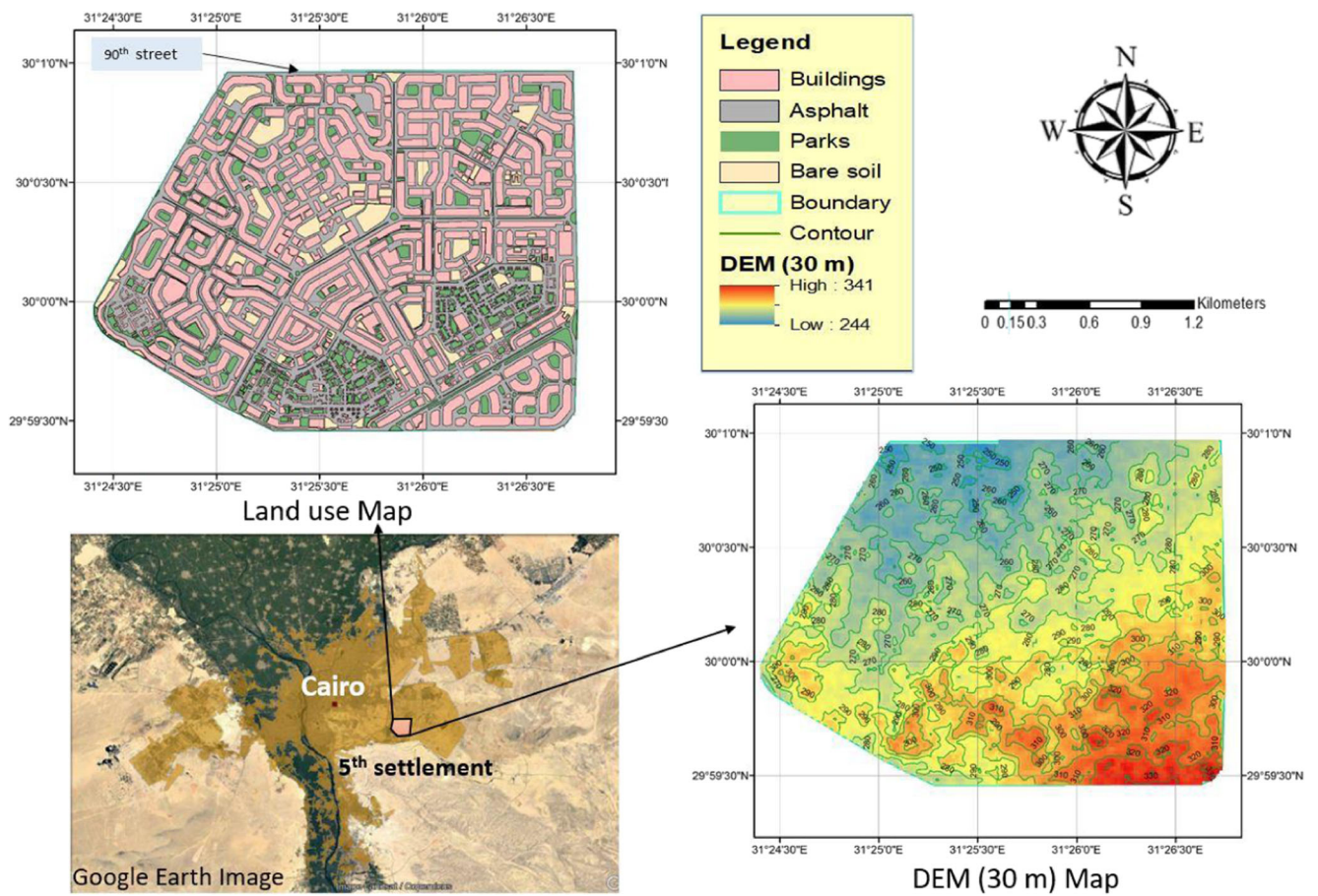


Fig. 6 Maps of land use and DEM of the 5th settlement region, Cairo

Fig. 7 Main aquifer systems in Egypt (Source: MWRI 2005)

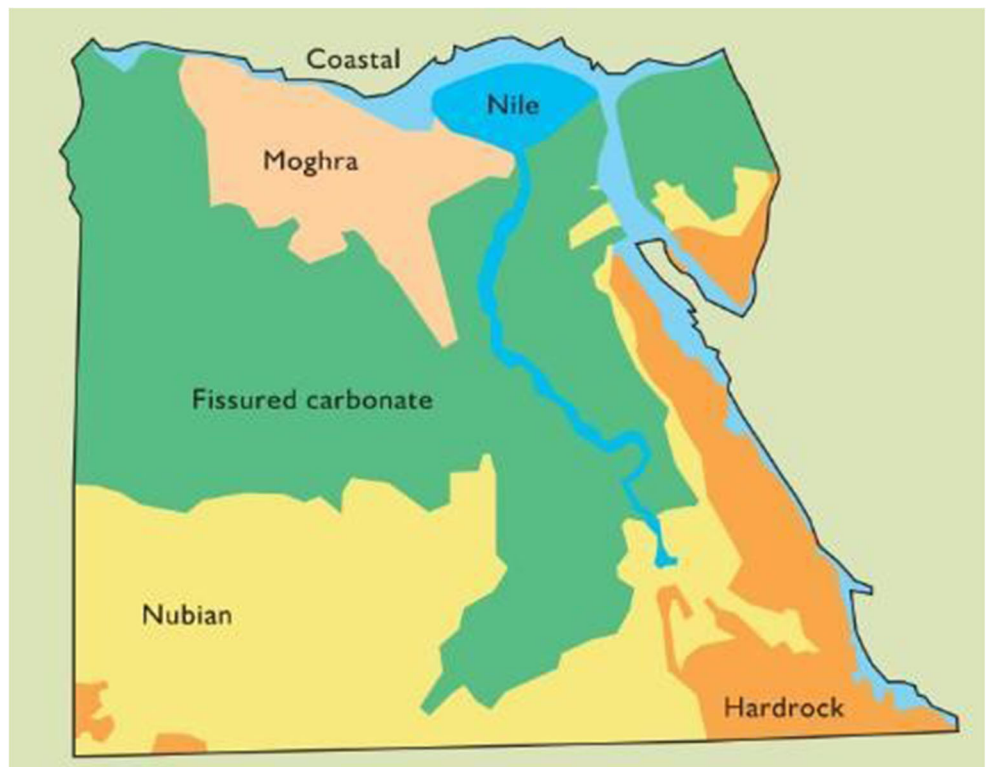


Table 7 Spatial fraction of different land covers in the 5th settlement region (Cairo) and its impact on $I_{c(eff)}$ and groundwater recharge in both No–RWH and RWH cases

Land cover	Surface area [m ²]	Spatial fraction of land cover	Infiltration coefficient (I_c)	
			No–RWH	RWH
Park	1100447	9%	35%	35%
Asphalt	5179716	43%	5%	80%
Buildings	5094827	43%	5%	80%
Bare soil	621651	5%	50%	50%
Total	11996641	Calculated $I_{c(eff)}$	10%	75%
		Calculated groundwater recharge [m ³ /year]	50386	377894

extends from October to March and rainfall peaks arise on December, January, and February. The annual volume of rainwater harvested can reach, on the average, 142.5 MCM in only 22 studied cities. The results demonstrate that the potential water savings from the share of RWH in some regions to their future supplementary needs of domestic water can be substantial. The maximum water saving occurred in Alexandria (located on the North), where RWH can satisfy around 12% of the future additional domestic water needs in the city. However, the potential for saving in the middle and south of the country is insignificant.

The groundwater recharge and surface runoff estimation were analyzed in a case study for the 5th settlement region in Cairo, for two situations: No–RWH and RWH system by implementing recharge wells. The results indicate that

execution of recharge wells to store rainwater into groundwater has a significant impact on the regional water cycle. The implementation of RWH system can increase the effective infiltration coefficient from 10% (No–RWH) to 75% (RWH) in the case study. As a result, this will increase the groundwater recharge by about 650% higher than that of the No–RWH condition. For surface runoff estimation, the runoff coefficient can decrease from 0.8 for the case of No–RWH to 0.15 for the case of RWH. This may decrease the volume of runoff in the case study by around 82% lower than that of the No–RWH condition. Hence, this will lead to a significant reduction in risks of flooding and the expenses of the municipal drainage system installation and operation in the region. In addition, for most Egyptian cities, rainfall sewer systems are not effectively working or even nonexistent, and the construction cost of

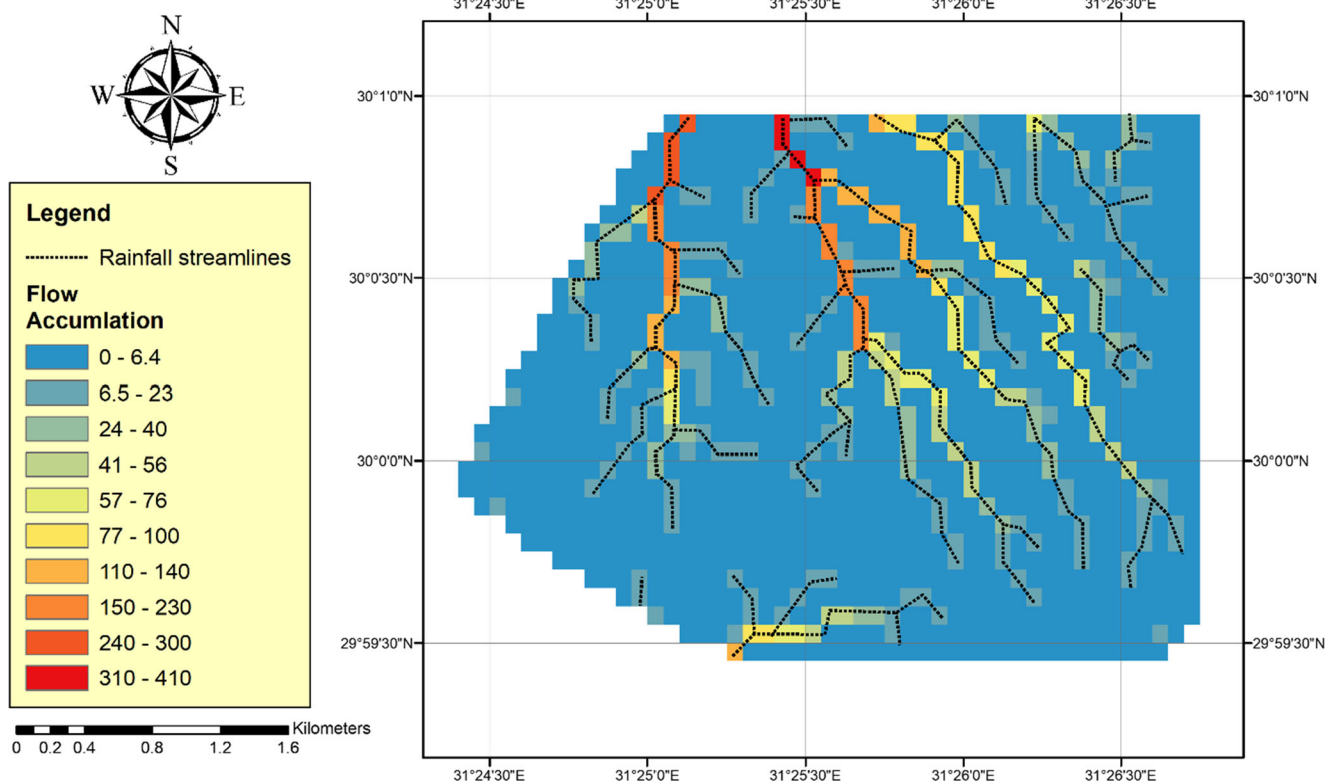


Fig. 8 Flow accumulation map of the 5th settlement region, Cairo

traditional systems of RWH (e.g., underground tanks) is extremely high. Therefore, the implementation of RWH that include recharge wells could be an economical solution to increase groundwater storage and alleviate suffering from inundation problems in urban environments.

Although the case study is based on data from only 22 cities in Egypt, the inferences made in this paper represent a starting point with respect to the feasibility of RWH in the country. Thus, a recommendation for future studies is directly related to include more cities to have clear picture of the potential of RWH in Egypt. Furthermore, a thorough study on the construction of infiltration wells should be conducted in different urban environments in Egypt, to consider certain characteristics in views of geology, hydrology, climatology, and topography. Additionally, the spatial position of the recharge wells is an important aspect of the design of such RWH systems.

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