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Rainwater Harvesting from Urban Coastal Cities Using Recharging Wells: A Case Study of Egypt

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ABSTRACT

Rainwater harvesting is becoming increasingly popular among urban planners across the world as a source of alternative water in integrated water resource management plans. In this study, to mitigate urban inundation, to avoid rainfall mixing with municipal sewerage, and harvest rainwater, a design methodology for artificial recharge well in urban areas is proposed. A brief summary of some Egyptian governorates that harvested rainwater and the corresponding techniques for rainwater harvesting are presented. Five case studies from Egyptian coastal cities were chosen to examine rainwater harvesting (RWH) using recharging wells systems: Marsa Matrouh, part of Dabaa, Zaheria region in Alexandria, part of Baltim, and 1st Department Region in Al-Arish. Groundwater recharge and surface runoff volumes are evaluated in two scenarios: the number of RWH and no RWH. A comparison between harvested volumes of water corresponding to these two conditions is presented and analyzed. The proposed design and construction of the recharge wells show a recharge well diameter of 0.45 m, discharge of 25.8 m^3/h in sandy strata of a depth of 20 m from the ground surface, and a permeability coefficient of 25 m/day. Using the recharge wells system significantly impacted the regional water cycle and reduced saltwater intrusion in coastal aquifers. Recharging rainwater in local aquifers beneath cities via recharging wells is the most cost-effective method for RWH from metropolitan areas.

Keywords: Water resources, Rainwater harvesting, Coastal aquifers, Saltwater intrusion, Recharging wells.

1. INTRODUCTION

In old cities, the quantities of rainfall will flow into the sewerage networks that are designed to drain only limited amounts of rainfall. In extreme rain events, the sewerage networks may be over-flooded which may lead to ecologic and economic hazards.

Rainwater must be completely separated from the sewage networks because the current rainwater causes a burden on the sewage treatment plants, as well as a large loss of electrical energy during treatment.

Some coastal cities in Egypt, witnessed many cases of drowning and the rains every year always constitute a burden on the sewage stations. Rainwater harvesting (RWH) is the collection, storage, distribution, and usage of rainwater for a range of purposes, including drinking and domestic uses, irrigation, industry, and livestock grazing, as well as reducing the load on sewage treatment plants [1, 2].

RWH in urban environments can be performed by using rainwater sewer networks to collect the rainwater from large surfaces and rooftops and store it in under or above ground tanks [3, 4]. The construction cost of these tanks is extremely high and required several free spaces and complicated pumping system. The most alternative economical technique for RWH is recharging the rainwater in local aquifers below the city via recharging wells [5].

This technique is more efficient as it fairly and equally distributes the rainwater resource between the whole city population. A large portion of rainwater is often lost in peak flows to runoff to the outlets of catchments. RWH is necessary to use this runoff and it is an ancient traditional technique that was and is still practiced in many parts of the world especially in arid and semi-arid regions (ASARs) [6, 7].

Populations of ASARs have developed a variety of traditional RWH techniques to increase the amount of available water and consequently overcome the problem of water scarcity [8]. Climate change has become a serious global problem, and its effects on getting water are clearly visible in developing countries [9, 10].

RWH is also considered as a strategic way to mitigate the effects of climate change and its effect on water availability in ASARs. Thus, there is a need for a robust methodology for assessing RWH potential and identifying appropriate areas for these technologies. In urban regions, runoff is harvested in available open areas such as landscapes; open fields; parks; gardens; roads and pavements; driveways; and others. The collected rainwater in these areas can be drained via two methods [11]. The first one is the traditional method in the oldest cities in which, sewage water pipe network is used. The second method is the rainwater sewer networks that are implemented in the new cities which are used to collect the rainwater and stored in storage facilities (i.e., under or above ground tanks) to use it, after the necessary purification, as a water resource. Without RWH, several damages can be occurred such as

(i) various pollutants (sediments, toxic chemicals, debris, nutrients, and litter) may be moved to nearby residential areas [12], (ii) anthropogenic pollutants, heavy metals, bird droppings, and animal waste can be transferred from roads and roofs into downstream water [13], and (iii) flows of stormwater runoff over urban impervious surfaces cause flooding, traffic problems, and heavy casualties [14, 15]. Accordingly, the life of urban dwellers, the aquatic environment, and hydrology can be impaired [16].

The main objectives of the study are to utilize the rainwater in groundwater recharge in addition, the other multipurpose activities, as avoiding rainwater discharge in the municipal sewers, developing a policy for appropriate rainwater harvesting system in the Egyptian coastal cities, designing rainwater harvesting techniques (collection, storage, and groundwater recharge) under the various local conditions, and to find out a solution to deal with ponding of rainwater in these cities. The workflow methodology consists of (1) an overview of the different techniques used for rainwater harvesting, (2) it is reviewed the dependence on RWH for groundwater recharging and the saltwater intrusion in coastal regions, (3) the average monthly and annual rainfall data in the Egyptian coastal cities is collected and a five case studies were chosen to investigate rainwater harvesting (part of Marsa Matrouh city, part of Dabaa city, Zaheria region in Alexandria city, part of Baltim city, and 1st Department Region in Al-Arish city), estimation of volumes of RWH potential from roof of buildings and roads runoff in two cases of no-RWH and RWH conditions, and (4) a design methodology of recharge well and harvesting rainwater is presented.

2. MATERIALS AND METHODS

2.1 Techniques of RWH

Ponds, check dams, terraces, percolation tanks, and Nala bunds are the most popular techniques used in non-urban/rural regions to collect water resulting from surface runoff. Ponds are considered the most economical and reliable source of water in ASARs. They are suitable when rainfall intensity is less than 200 mm/year; earth slope is less than 5%; soil type is silty loam and sandy clay loam; land use is moderately cultivated, shrubland and scrubland; and the catchment area is less than 2 ha. Harvested pond’s water is used either for irrigation, domestic uses, livestock grazing, controlling erosion, or stabilizing water canals. Ponds are formed by constructing an embankment across a watercourse and excavating a pit to block and store the runoff rainwater [8]. Check dams: they are small impermeable dams constructed across water canals in narrow wadis with mild slopes. Check dams are suitable for rainfall intensity is less than 1000 mm/year; earth slope is less than 15%; soil type is sandy clay loam; land use is shrubland and the Barren land; and catchment area is greater than 25 ha. Such dams are cheap to construct, but the number of favourable available locations is limited. Also, they can be constructed using local materials and labour and they provide a valuable source of water. They are widely used in many parts such as Iraq, Tunisia, China, and India [17]. Terraces are constructed on the earth of steep slopes and they are formed by retaining walls. Terraces are suitable for rainfall intensity ranging between 200 mm/year to 1000 mm/year; earth slope ranged between 5% and 30%; soil type is clay loam and sandy loam, and land use is Bushland with scattered trees and shrubland. In Yemen, terraces are the most used RWH systems [8]. Terraces’ walls are built of stone with spacing between stones which allow movement of water to successive ones without eroding the soil. Percolation tanks are surface water bodies artificially created in permeable lands to facilitate recharging the surface runoff to the groundwater [17]. Percolation tanks are suitable for rainfall intensity is less than 1000 mm/year; earth slope is less than 10%; soil type is silt loam and clay loam; land use is barren or scrub land; and the catchment area is greater than 25 ha [8]. Nala bunds are embankments constructed in areas with mild slopes across streams [18]. Nala bunds are suitable for rainfall intensity is less than 1000 mm/year; earth slope is less than 10%; soil type is silt loam; land use is barren land; and the catchment area is greater than 25 ha [8]. Rooftop RWH is used to capture and store rainwater from roofs [19, 20].

2.2 Dependence on RWH for groundwater recharging

Reduction of rainfall infiltration is one of the major concerns in urban hydrology to decrease groundwater recharges, increase flooding risks, and accelerate pollutants transportation [10, 21]. To improve the performance of integrated urban water systems, many studies were conducted. For example, Behzadian et al. [22] assessed the use of smart RWH techniques to mitigate local floods and supply harvested rainwater. Also, recharging local aquifers through directing rainwater infiltration wells is a new technique of RWH [23, 24]. Gado and El-Agha [10] discussed the probability of using RWH for groundwater recharge and consequently improving the infiltration ratio. They compared the values of infiltration ratio for no–RWH and RWH conditions when applying on the 5th settlement region in Cairo.

Surface runoff estimation for the two conditions is also discussed. In recent studies, increasing the infiltration in urban areas can be carried out by providing permeable lawns in each house, provision of permeable pavements, construction of permeable walkways, provision of rain gardens, provision of grass swales, urban forestry applications, mulched areas, use of permeable concrete where possible, and directing downspouts and gutters towards permeable areas [25, 26]. However, it is worth mentioning that as per literature published at the international level this technique is not in common practice in Egypt and needs some research work as well as awareness to use such modern techniques for stormwater management.

2.3 Saltwater intrusion

Recharging coastal aquifers using RWH has also a great advantage for decreasing saltwater intrusion [27]. Saltwater intrusion is commonly occurring in coastal areas when depending on groundwater as a water source. Excessive pumping to supply the growing population leads to the increase of saltwater intrusion problems. Coastal aquifer excessive pumping causes the lowering of the water table of the freshwater body below the adjacent seawater wedge. Accordingly, the interface advances inland until a new equilibrium is reached. One of the methods used to control the saltwater intrusion in coastal regions is groundwater recharging by the implementation of recharging wells. Groundwater recharging aims to increase the groundwater table for unconfined aquifers and piezometric surface for confined aquifers. Various researchers tackled the problem of saltwater intrusion in coastal aquifers. For example, Kashef [28] studied the effect of wells recharging on saltwater retardation in confined coastal aquifers. Recharge wells were located parallel to the shoreline at various distances. It is concluded that batteries are optimally located when they are spaced by 0.7 L and L (L is the initial length of intruded saltwater wedge). Also, the effect of injection wells on saltwater intrusion in confined coastal aquifers was studied by Mohammed et al. [29] where the sharp interface is assumed and a quasi-three-dimensional finite element model is used. Various conditions are studied through changing well spacing: intensity and freshwater injection duration. They concluded that proper selection of injection rates and well spacing could reduce up to 60-90% of seawater intrusion. Abd-Elmaboud [30] developed a finite element model to present a proper solution for the problem of saltwater intrusion using injection wells.

The application is carried out on the Quaternary Aquifer of Delta Wadi El-Arish, Sinai. He concluded that, during the initial stage of injection, the movement of the interface toe is vigorous, and slows down with time as it approaches the steady-state. Also, increasing injected water decreases the intruded zone until reaches at certain value; and an increase in the injection rate has an insignificant effect on the reduction of the interface toe. Armanuos et al. [31] investigated the efficiency of using injection wells to control saltwater intrusion in unconfined aquifers of sloping beds. They carried out a sensitivity analysis to study the confining layer bed slope change. The application on a case study of Akrotiri showed the effectiveness of injection wells to mitigate the saltwater intrusion in sloping bed aquifers.

2.4 Study area

Five case studies in Egyptian coastal cites part of Marsa Matrouh, part of Dabaa, Zaheria region in Alexandria, part of Baltim, and 1st Department region in Al-Arish city are chosen to estimate the annual volumes of RWH which may use for groundwater recharge. The two factors that increase the stress on the availability of water resources in urban areas are climate change and the growing population. The chosen case studies overlie the coastal aquifer (Figure 1), which contains several local aquifer systems and covers a zone of about 10,000 km^2. Table 1 summarizes water and soil characteristics of the coastal aquifer [32]. The coastal aquifer is recharged by rainfalls and it consists of water-bearing formations of coastal dunes, and bars, wadi deposits, calcarenites and shallow marine sands. These formations run along the north coast (both western and eastern parts). Along with some locations on the Red Sea, there are local reservoirs, mainly geological structure origin of Tertiary and pre-tertiary. They are located at EL-Qaa and Ayoun-Moussa in Sinai and also at Shagar, Safaga, Quseir, Ras-Perasand Halayib in the Eastern Desert [32]. In the Mediterranean coastal aquifer, the water salinity is affected by saltwater intrusion and the rate of flow from this aquifer to the sea is about 1.5 m^3/day. Four mainland cover components are distinguished in each studied urban city: buildings, asphalt areas, parks, and bare soil. The ArcGIS software (https://www.arcgis.com/index.html) is applied to each study area to produce the land-use map and consequently, the area of each component is digitized by high-resolution Google earth images.

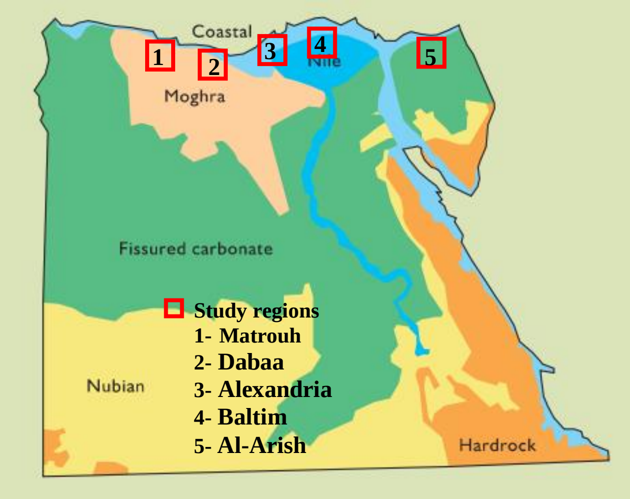


Figure 1: The major aquifer systems in Egypt. Source [33]

2.5 Rainfall **data in coastal Egyptian cities**

Gado and El-Agha [10] presented rainfall data for 11 stations throughout coastal Egyptian cities. The rainfall record length ranges from 18 years at Hurghada station to 55 years at Alexandria station, with an average of 29 years. Monthly and annual rainfall data (total rainfall and a total number of rain days) were considered. In Egypt, the average rainfall (monthly and annual) in the studied stations is shown in Table 2. The spatial variation of the average annual total precipitation is shown in Figure 2. The overall average annual rainfall is 80.45 mm (varies from 10 to 172 mm). On the North Coast, average annual rainfall exceeded 100 mm at Alexandria (172 mm), Baltim (140 mm), Marsa Matrouh (122 mm), and Dabaa (112 mm) stations. As such, significant amount of rainwater can be harvested in these locations. The rainfall intensity decreases to the east at Port-Said to be 99 mm/year. The average annual precipitation over coastal part in Sinai Peninsula, according to the available data, is generally less than 100 mm. In the northern zone at El-Arish, the average annual rainfall is equal to 87 mm/year. The yearly rainfall in other coastal cities in the Red Sea strip, according to the available data, ranges between 45 mm/year at Hurghada and 10 mm/year at Ras Sedr. The annual rainy days in the North Coast exceeded 20 days at six stations: Alexandria (33 days), Baltim (31 days), Dabaa (30 days), Marsa Matrouh (28 days), Port Said (23 days), and Al-Arish (20 days). The average monthly rainy days ranges from nine days at Alexandria and Baltim in January and 0 day in several cities especially through summer months. As such, the Egypt's rainy season extends from October to March, with the peak precipitation during December, January, and February [9].

2.6 Prospects of RWH from Coastal Egyptian Cities

During specific storm events, various coastal Egyptian cities are exposed to significant amounts of rainfall, where it may lead to flash floods and inundations problems. As such, to overcome these problems, RWH from these cities have to be carried out. Also, this harvested rainwater can be used in the water resources system to decrease the growing gap between supply and demand, due to increasing of population. Several factors affect RWH: pattern and intensity of rainfall; variation of seasons; topography; evapotranspiration; type of soil and its holding capacity for water; attachments area and its location; and land use. The annual volume of RWH from coastal cities can be calculated from the rational method:

$$\mathrm{AVR} = (\mathrm{AR} \times \mathrm{A} \times \mathrm{C}/1000) \qquad (1)$$

in which, AVR is the annual volume of rainfall that can be harvested from an urban area (m^3/year), AR is the average annual of rainfall (mm/year), A is the urban area (m^2), and C is a runoff coefficient (it taken equal to 0.8) [10]. Construction of recharging wells for RWH has to account for the hydrological and climatological conditions at the site, in addition to the surface area of the collection surface. To ensure that RWH is efficiently infiltrated into the aquifer without over flood, it should construct the infiltration well sufficiently deep with a filter length long enough to enable sufficiently high-water flow from the well into the ground, while considering the hydrogeological properties of the medium at the specific site of infiltration. Coefficients of infiltration are usually used to calculate the ratio of rainfall that may infiltrate the subsoil. Several factors affect the coefficients of infiltrations such as: land use, vegetation, topography, and soil properties [10]. As each selected urban coastal area having different land cover components (i.e., buildings, asphalt areas, parks, and bare soil), the effective coefficient of infiltration (I_{eff}), Equation 2, can be used.

$$I_{eff} = \frac{\sum_{i=1}^{nc} A_i \times I_i}{A_t} \qquad (2)$$

in which, A_i is the area of component i of land cover, I_i is the coefficient of infiltration corresponding to component i of land cover, A_t is the total urban area, and nc is the number of components (= 4).

Table 1: The characteristics of the coastal aquifer (Abdel-Shafy and Kamel [32])

Region	Groundwater table depth (m)	Saturated thickness (m)	Depth to water table (m)	Hydraulic conductivity (m/day)	Porosity (%)	Salinity (ppm)
Northwest coast	0	< 5	± 15	15 – 25	> 30	1000 – 6000
El-Qaa plain	50 – 100	60 – 80	50 – 70	5 – 10		600 – 2500
El-Arish aquifer	15 – 30	40 – 50	0 – 30	5 – 20		1500 – 6000

Table 2: Average monthly and annual rainfall (mm) in the Egyptian coastal cities (Gado [9]).

month City	1	2	3	4	5	6	7	8	9	10	11	12	Annual
Al-Arish	23	16	20	8	10	2	3	25	0	9	8	19	87
Alexandria	47	30	16	6	4	4	15	17	7	16	30	46	172
Baltim	40	37	14	5	4	0	4	0	26	14	13	34	140
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
Hurghada	8	1	34	1	43	3	5	34	70	30	32	54	45
Kosseir	5	11	2	6	9	2	12	73	20	6	3	3	21
Marsa Matrouh	32	21	11	9	9	20	4	0	5	18	19	34	122
Port Said	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

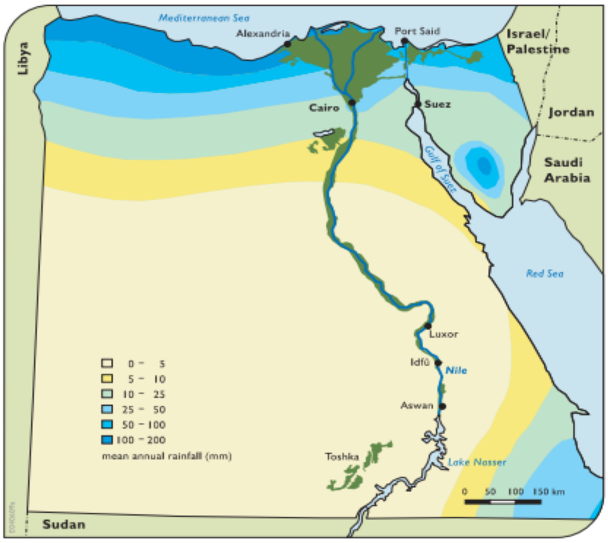


Figure 2: Spatial distribution of mean annual precipitation in Egypt.
Sources: [33].

2.7 Estimation of required recharge wells and ponding area clearance time

During the rainy season (winter), digital elevation model and flow accumulation maps, and interviews with local residents were conducted to gather information regarding the current drainage system, ponding depth and area, ponding time, and local residents' opinions and suggestions. The field study assisted in determining the possibilities for rainwater collection from important highways with crucial ponding depths. The methodology's second section addresses the use of rainwater harvesting for artificial groundwater replenishment. The following primary factors that induce the establishment of ponding regions were addressed based on field observation and interviews with local residents. (i) Inadequate sewer/drain capacity, (ii) sewer/drain siltation, (iii) no provision of the inlet, (iv) no provision of sewer, (v) depressions converging to a specific location, and (vi) topographic variation within city areas, as some areas are in depressions that form the ponding area. Unlevelled roads are the most common cause of ponding areas. Recharging flow (Q_R) by constant head recharge in bore well is calculated as:

$$Q_R = 2.75 \times h \times D \times K \qquad (3)$$

where, h is the depth of pervious sand strata from ground level = 20 m; D is the diameter of recharge well (m) = 0.45 m, and K is the coefficient of permeability depending on the soil type (for sandy soil = 25 m/d). Based on Equation 3 and values of parameters the recharging capacity of the well was estimated as 25.8 m^3/h. The ponding area runoff clearance time was calculated based on the flow rate formula.

$$Q_R = \frac{V}{T} \qquad (4)$$

where, Q_R = Recharge rate (m^3/h); V = Runoff volume (m^3), and T = Clearance time (h).

3.RESULTS AND DISCUSSION

The ArcGIS software was applied to obtain google earth maps, digital elevation model maps, and the land use maps for the five studies regions Marsa Matrouh, Dabaa, Alexandria, Baltim, and Al-Arish. From these maps the computed urban areas were 65,108,998, 14,530,085, 432,854,534, 6,463,888, and 39,884,373 m^2

for Marsa Matrouh, Dabaa, Alexandria, Baltim, and Al-Arish respectively. Figures A1 to A5 show these maps. From the digital elevation model maps, the land topography slope is computed and from land-use maps the asphalt roads, parks, buildings, bare soil, and asphalt areas were computed. Table 3 summarizes the characteristics of each study urban coastal area are in terms of the area of each land cover component, total area, and land topography slope.

3.1 Estimation of infiltration coefficient

In the selected five case studies, the groundwater recharge estimation is studied in the case of no-RWH and RWH conditions via the installation of recharging/infiltration wells. In the case of No-RWH, coefficients of infiltration (I), Equation 2, corresponding to the land cover component are taken equal to 0.05, 0.05, 0.35, and 0.5 for buildings, parks, asphalt areas, and bare soil respectively. While the corresponding values are assumed equal to 0.8, 0.8, 0.35, 0.5 respectively in case of RWH occurs [10]. For each study urban area shown in Table 4, the values of estimated I_{eff}, Equation 2, and the corresponding volumes of groundwater recharge, Equation 1, for both No-RWH and RWH conditions are calculated.

Table 3: Estimated spatial fraction of different land covers and land topography slop for the case studies

Case study	Area of land cover component (m^2)				
	Buildings	Asphalt area	Parks	Bare soil	Total area
Part of Marsa Marouh city	5,711,067	916,221	190,309	942,377	7,759,974
	85.4%		2.5%	12.1%	
Part of Dabaa city	939,638	356,478	153,574	334,375	1,784,065
	72.6%		8.7%	18.7%	
Zaheria region, Alexandria city	696,923	431,417	167,721	663,856	1,959,916
	57.6%		8.6%	33.8	
Part of Baltim city	780,799	438,198	501,051	672,209	2,392,257
	51%		20.9%	28.1%	
1st Department Region, Al-Arish city	4,028,135	2,361,607	2,358,513	4,750,216	13,498,471
	47.3%		17.5%	35.2%	

The volume of groundwater recharge is calculated, using Equation 1, by replacing coefficient C with I_{eff}. The following remarks are noticed from Table 4: (i) for the study part of Marsa Matouh city, by comparing No-RWH with RWH system, both the estimated I_{eff} and the annual volume of groundwater recharge may increase from 11% to 75% and from 104139 m^3 to 710038 m^3 respectively. Thus, I_{eff} increases with a factor of 6.8 and consequently the volume of groundwater recharge increases by about 582% due to implementation of recharging wells, (ii) by comparing no-RWH with RWH system for the study part of Dabaa city, both the estimated I_{eff} and the annual volume of groundwater recharge may increase from 16% to 71%, and from 31970 m^3 to 141869 m^3 respectively. Thus, I_{eff} increases with a factor of 4.4 and consequently, the volume of groundwater recharge increases by about 344% due to implementation of recharging wells, (iii) for Zaheria region in Alexandria city, both the estimated I_{eff} and the annual volume of groundwater recharge may increase from 23% to 66% and from 77534 m^3 to 222490 m^3 respectively. Thus, I_{eff} increases by a factor of 2.9, and consequently the volume of groundwater recharge increases by about 187% due to implementation of recharging wells, (iv) by comparing No-RWH system with RWH in the study part of Baltim city, both the estimated I_{eff} and the annual volume of groundwater recharge may increase from 24% to 62% and from 80380 m^3 to 207648 m^3 respectively. Thus, I_{eff} increases by a factor of 2.6, and consequently, the volume of groundwater recharge increases by about 158% due to implementation of recharging wells, and (5) also, for 1st Department Region in Al-Arish city, both the estimated I_{eff} and the annual volume of groundwater recharge may increase from 26% to 62% and from 305335 m^3 to 728108 m^3 respectively. Thus, I_{eff} increases by a factor of 2.4, and consequently, the volume of groundwater recharge increases by about 138% due to implementation of recharging wells. The maximum difference between the values of I_{eff} corresponding to No-RWH and RWH system conditions is found to be at the study part of Marsa Marouh city while, the minimum difference is at 1st Department Region in Al-Arish city, Table 4. This is due to the spatial fractions of both building and asphalt areas components being equal to 85.4% and 47.3% for the study part of Marsa Marouh city and 1st Department Region in Al-Arish city respectively, Table 3. The spatial fractions of these two components are equal to 72.6%, 57.6%, and 51% for the study part of Dabaa city, Zaheria region in Alexandria city, and the study part of Baltim city respectively, Table 3. The increase of this spatial fraction the I_{eff} value increases because the infiltration coefficient I changed for both building and asphalt areas from 0.05 (case of No-RWH) to 0.8 (case of RWH occurs) while, the I value corresponding to both parks and bare soils remain the same for the two conditions. Groundwater recharging using the harvested rainfall in coastal regions has a significant impact on the region's water cycle and, at the same time, it can minimize the intrusion of seawater. Also, the installation of wells to recharge RWH for groundwater can be considered an economical solution than the installation of a rainfall sewer network [10]. The implementation of recharging wells for RWH has two main benefits for the urban hydrological system: increasing groundwater recharge; and decreasing surface runoff volumes as will discuss later. Also, the annual volume of groundwater recharge is considered a water resource stored in the aquifer and can depend on it for several purposes. Thus, using the recharging wells technique can increase this source with percentages 582%, 344%, 187%, 158%, and 138% respectively for the study five areas.

Table 4. Values of I_{eff} and volume of groundwater recharge for the selected case studies

Case study	Effective coefficient of infiltration (I_{eff}), Equation 2		Annual volume of groundwater recharge (m^3), Equation 1	
	No–RWH	Existing RWH	No–RWH	Existing RWH
Part of Marsa Marouh city	11%	75%	104,139	710,038
Part of Dabaa city	16%	71%	31,970	141,869
Zaheria region, Alexandria city	23%	66%	77,534	222,490
Part of Baltim city	24%	62%	80,380	207,648
1st Department Region, Al-Arish city	26%	62%	305,335	728,108

Table 5. Maximum values of the accumulated flow and annual volume of surface runoff for the selected case studies

Case study	Max. value of the accumulated flow	Annual volume of surface runoff (m^3)	
		No–RWH	Existing RWH
Part of Marsa Marouh city	2274	199,748	39,950
Part of Dabaa city	3115	251,194	78,498
Zaheria region in Alexandria city	1061	114,970	44,346
Part of Baltim city	378	33,340	15,241
1st Department Region in Al-Arish city	5987	328,147	159,386

3.2 Estimation of surface runoff

The increase in the difference between the I_{eff} values associated with No-RWH and RWH conditions and consequently the corresponding volumes of groundwater recharge (Table 4) lead to noticeable decreases in surface runoff and thus, the flood risks can be avoided [21]. To estimate the annual volume of surface runoff for each studied area, the topography of the studied coastal region is investigated using Digital Elevation Model with 30-m resolution. Figure 3 demonstrated the flow direction and flow accumulation maps for each study area. Also, the total numbers of pixels that will drain into outlets of each study area are counted. Table 5 summarized the maximum values of the accumulated flow and annual volume of surface runoff for both cases of No-RWH and the RWH conditions. For the study part of Marsa Marouh city, runoff coefficient; I_{eff}; and the ratio of evaporation and interception for the No-RWH are estimated to be 80%, 11%, and 9% respectively. While, the corresponding values for the RWH system are estimated equal to 16%, 75%, and 9% respectively. For the study area of Dabaa city, runoff coefficient; I_{eff}; and ratio of the evaporation and interception for No-RWH are estimated equal to 80%, 16%, and 4% respectively. While, the corresponding values for the RWH system are to be 25%, 71%, and 4% respectively. For the Zaheria region in Alexandria city, runoff coefficient; I_{eff}; and ratio of the evaporation and interception for No-RWH are estimated equal to 70%, 23%, and 7% respectively. While, the corresponding values for the RWH system are to be 27%, 66%, and 7% respectively. For the study part of Baltim city, runoff coefficient; I_{eff}; and ratio of evaporation and interception for No-RWH is estimated equal to 70%, 24%, and 6% respectively. While, the corresponding values for the RWH system are to be 32%, 62%, and 6% respectively. For the 1st Department Region in Al-Arish city, runoff coefficient; I_{eff}; and the ratio of evaporation and interception for No-RWH are estimated at 70%, 26%, and 4% respectively. While, the corresponding values for the RWH system are to be 34%, 62%, and 4% respectively. The results indicated that the maximum annual volume of surface runoff is at the following locations for each study area:

- Alam Al-Rum Street in the east and at the palace of Al-Qasr hotel on the road of Al-Qasr-Ajaybah Al-Gharam in the northwest, for the study Part of Marsa Marouh city, Figure 3a.
- Near Dabaa gas station on Alexandria-Marsa Matrouh Road in the northeast, for the study Part of Dabaa city, Figure 3b.
- Near Al-Salhiya school at the intersection of Al-Shuhada Square Street with the market station in the east, for Zaheria region in Alexandria city, Figure 3c.
- Near the Baltim wholesale market for vegetables and fruit in the northeast, for the study Part of Baltim city, Figure 3d.
- The end of Ali bin Abi Talib Street in the southwest and various areas on the Al-Arish Al-Hasanah Road in the east, for 1st Department Region in Al-Arish city, Figure 3e.

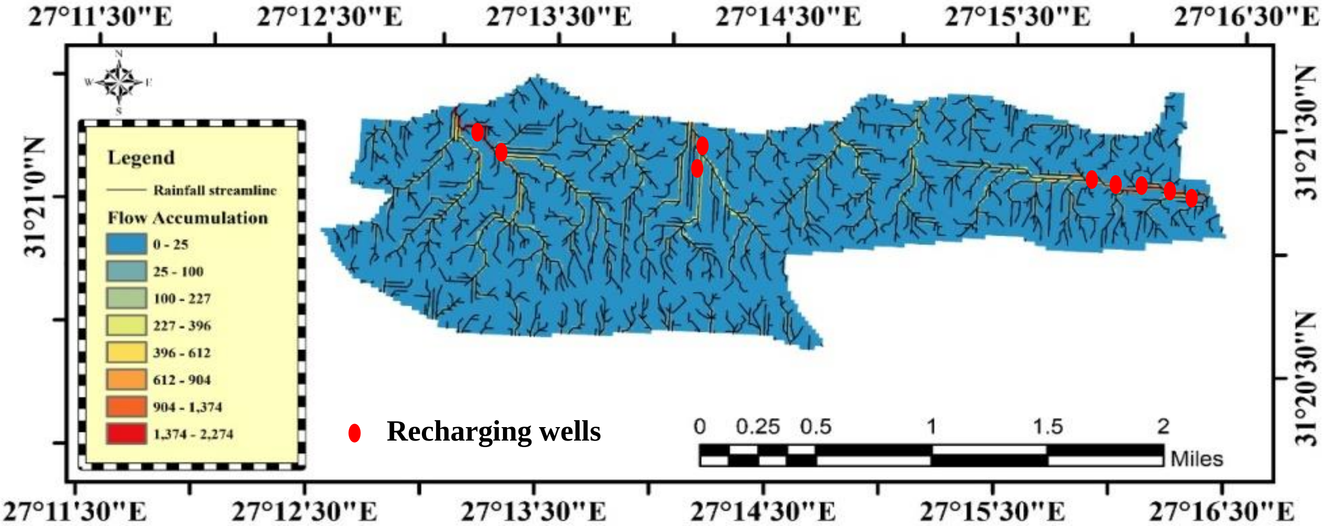
By comparing the annual volumes of surface runoff in both cases of No-RWH and the RWH system, Table 5, the following remarks are noticed:

- For the study part of Marsa Marouh city, the annual volume of surface runoff decreases by about 80% from RWH to No-RWH conditions.
- For the study part of Dabaa city, the annual volume of surface runoff decreases by about 69% from RWH to No-RWH conditions.
- For Zaheria region in Alexandria city, the annual volume of surface runoff decreases by about 61% from RWH to No-RWH conditions.
- For the study part of Baltim city, the annual volume of surface runoff decreases by about 54% from RWH to No-RWH conditions.
- For 1st Department Region, Al-Arish city, the annual volume of surface runoff decreases by about 51% from RWH to No-RWH conditions.

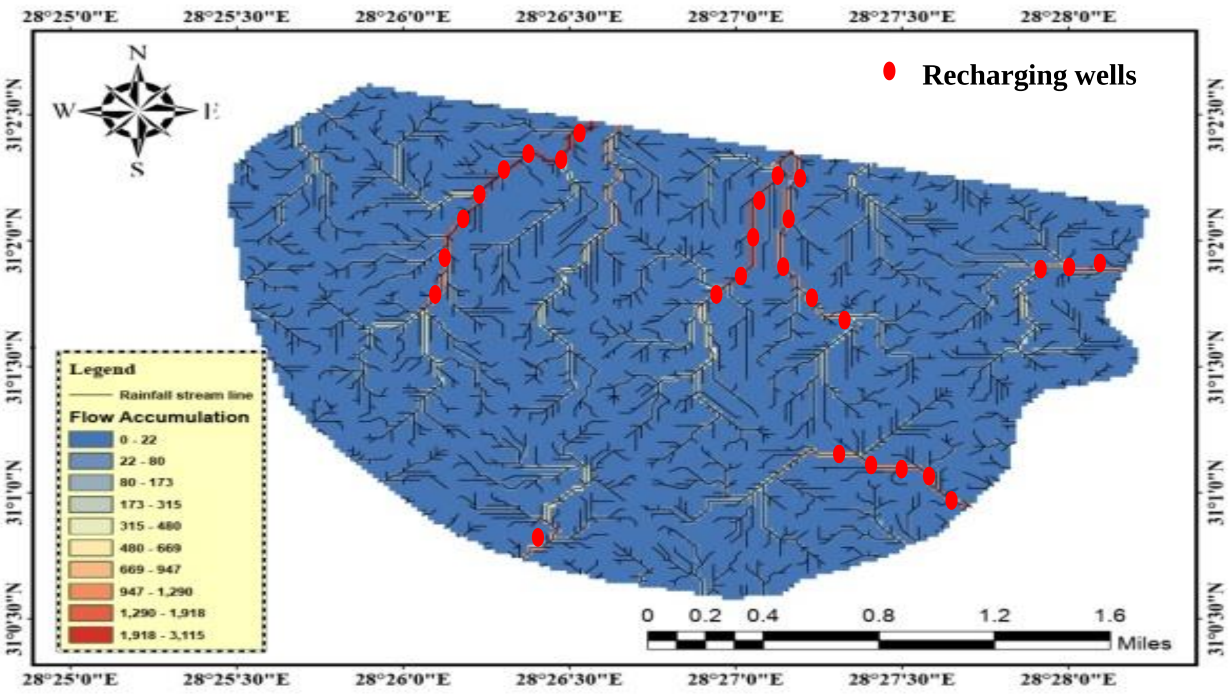
According to the previous analysis of reduction in surface runoff, the costs of the municipal drainage system installation and operation can be significantly reduced for each studied area especially, in Marsa Matrouh city.

3.3 Proposed design and construction of the recharge wells

Three main criteria guided the design of the recharging well. i.e., the design should be based on the location and available area, and standing water should be drawn down as quickly as possible into the groundwater table. Furthermore, the presence of contaminants in groundwater recharge must be limited or minimum as possible. The design concept is based on the idea that surface water runoff flows into a 2 m deep and 3 m wide subsurface tank. To avoid trash, clay, or any other choking material, this tank has a 2 m deep coarse filter mechanism. The horizontal filtering process recharges the groundwater with silt and clay-free water. Due to the head difference, the water will drain into the groundwater. As a result, the inflow rate will be roughly equal to the recharge rate. Figure 4 depicts a typical recharge well design with all parameters for a recharging capacity of 25.8 m^3/h to serve a ponding area of about 2.5 acres with a with ponding area clearance time with a drainage factor of 0.5. This style is employed in areas where traffic flow is minimal and there is no impediment to the flow of life. The groundwater recharge rate is high with this design because water flows in from the surface and quickly sinks down into the groundwater. As a result, the inflow rate will be roughly equal to the recharge rate, and the design structure will be straightforward to build and maintain. The problems of this design include those heavy metals will have minimal difficulty getting into subsurface water storage, resulting in water contamination. Heavy metals such as arsenic, lead, mercury, and cadmium are harmful to one's health, and the filtration material must be cleaned on a regular basis to keep the filtration process running smoothly. Adopting Egyptian’s water quality measures [33, 34] in design will improve the feasibility of this design method for replenishing the groundwater table. Because the soil is a natural filter material that cleanses precipitation before it enters the groundwater, the borehole pipe was kept 1.5 m above the water table. In addition, with the recharging chamber, silt trapping structures called as settling chambers were constructed where appropriate and necessary. These settlement chambers were used to filter rainwater for silt and other floating pollutants. Furthermore, in the event of excessive rainfall, bore well recharge rates may differ from rainfall rates. In such cases, the excess water is held in these chambers until it is absorbed by the recharge structure. As a result, the settlement chamber serves as a system buffer. In addition, Table 6 summarizes the estimated cost for this recharging well civil works, as the total cost is 98030 L.E. (6126 $). In the high rainfall accumulation area in the Marsa Matrouh, Dabaa, Alexandria, and Al-Arish regions the recharge wells distribution are as shown in Figure 3. Each well has a diameter of 0.45m and discharge of 25.8 m3/h in sandy soil strata (coefficient of permeability = 25 m/day). The distance between successive wells is 500 m, the well depth is determined based on the location of the groundwater table. Whereas, in Baltim city recharging wells will not be recommended due to the clay soil strata and small flow accumulation as shown in Figure 3 d compared to the other four regions.

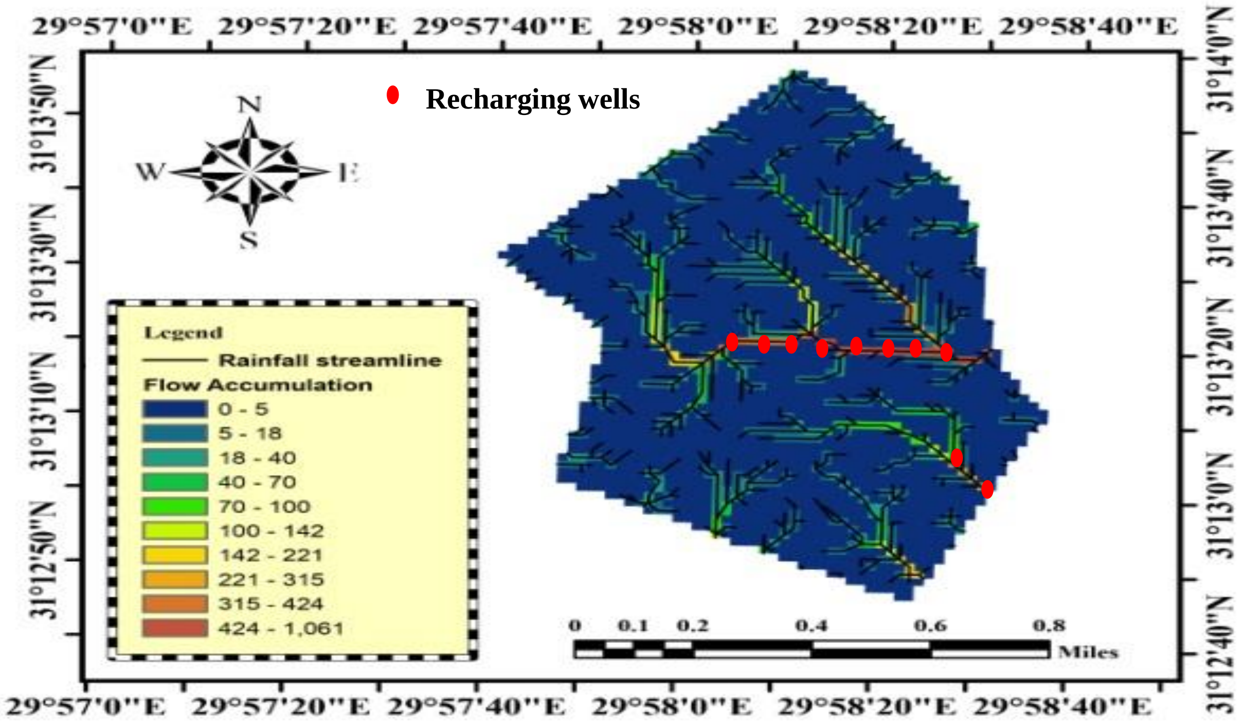


(a)



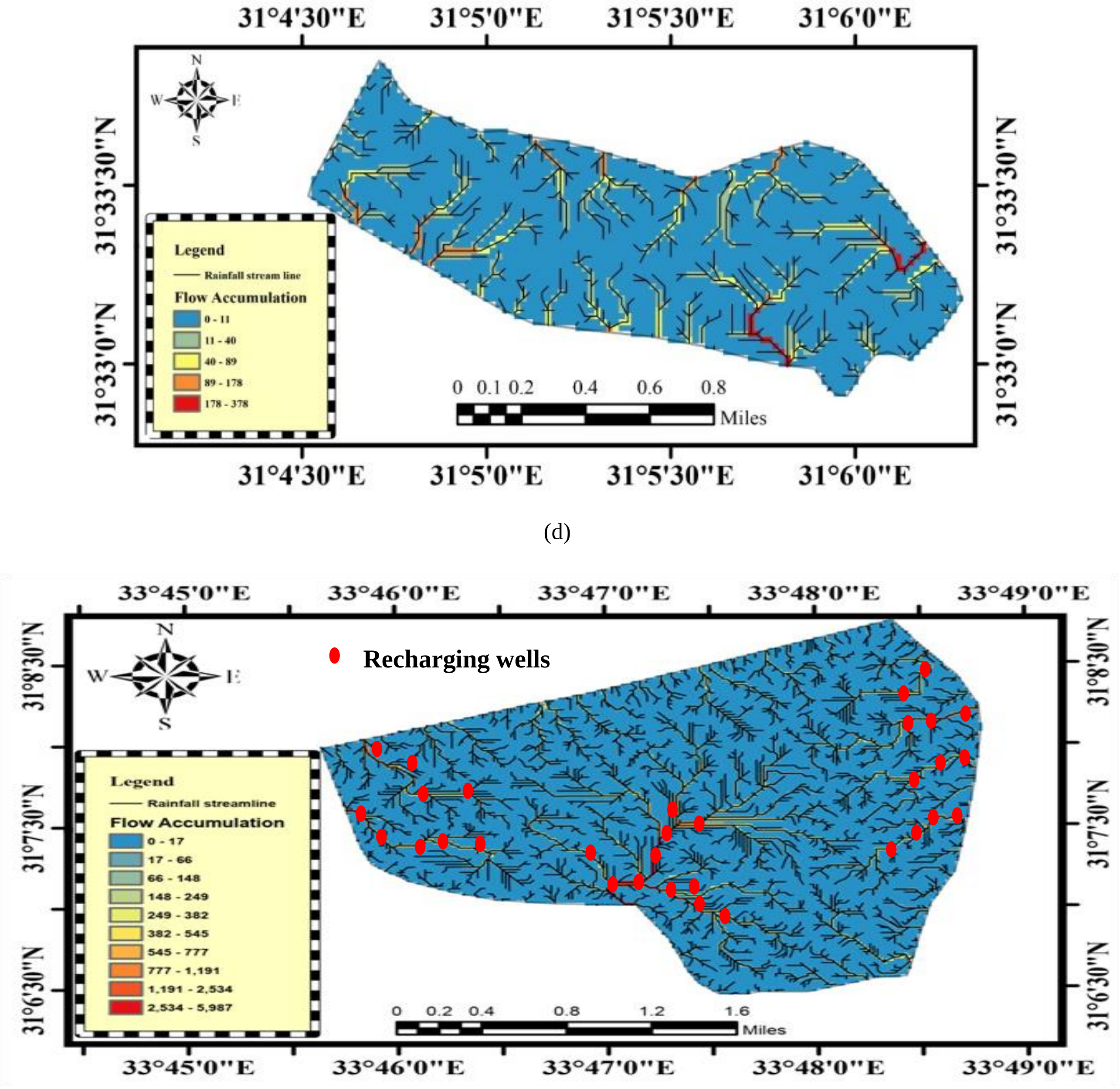
28°25'0"E
28°25'30"E
28°26'0"E
28°26'30"E
28°27'0"E
28°27'30"E
28°28'0"E
31°2'30"N
31°2'0"N
31°1'30"N
31°1'0"N
31°0'30"N
N
W
E
S
Recharging wells
Legend
Rainfall stream line
Flow Accumulation
0 - 22
22 - 80
80 - 173
173 - 315
315 - 480
480 - 669
669 - 947
947 - 1,290
1,290 - 1,918
1,918 - 3,115
0
0.2
0.4
0.8
1.2
1.6
Miles

(b)



29°57'0"E
29°57'20"E
29°57'40"E
29°58'0"E
29°58'20"E
29°58'40"E
31°14'0"N
31°13'50"N
31°13'40"N
31°13'30"N
31°13'20"N
31°13'10"N
31°13'0"N
31°12'50"N
31°12'40"N
N
W
E
S
Recharging wells
Legend
Rainfall streamline
Flow Accumulation
0 - 5
5 - 18
18 - 40
40 - 70
70 - 100
100 - 142
142 - 221
221 - 315
315 - 424
424 - 1,061
0
0.1
0.2
0.4
0.6
0.8
Miles

(c)



(d)

(e)

Figure 3: Flow accumulation maps for the case studies and proposed locations for the recharging wells: (a) Part of Marsa Marouh city, (b) Part of Dabaa city, (c) Zaheria region in Alexandria city, (d) Part of Baltim city, and (e) 1st Department Region in Al-Arish city

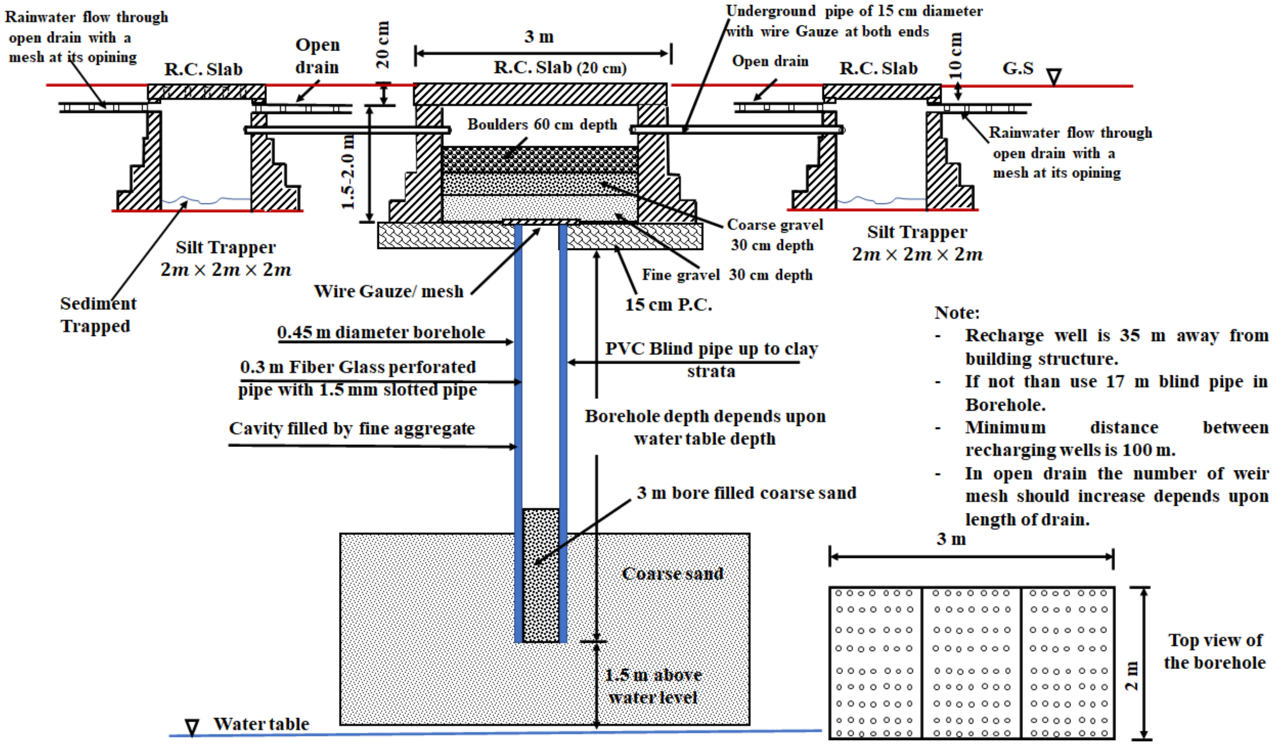


Figure 4: Proposed typical design rainwater harvesting (RWH) recharge well.

Table 6: Estimated cost for the recharging well civil works.

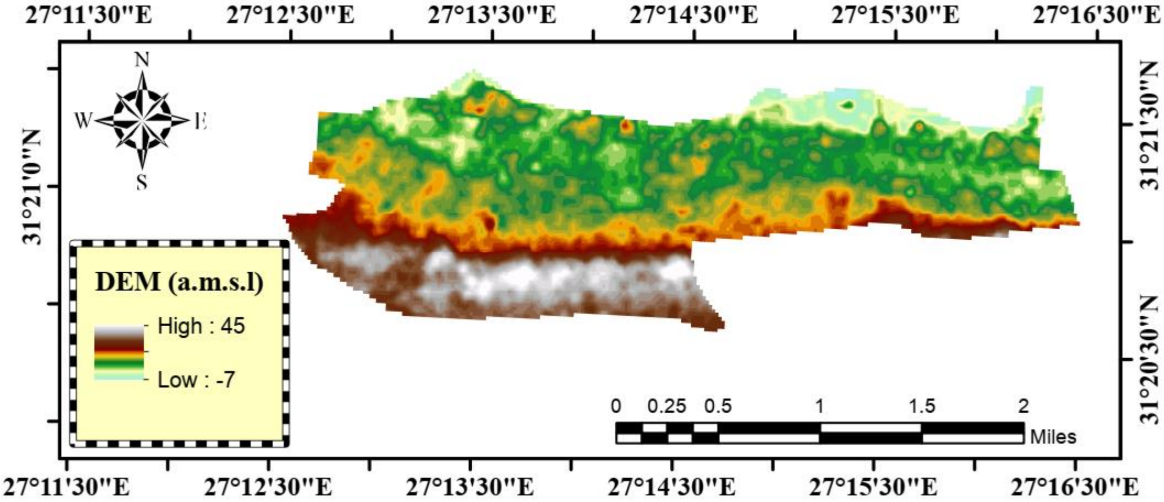
	Item works	Cost (L.E.)
1	Excavation	5000
2	Borehole drilling in all types of soil.	12000
3	Plain concrete	4000
4	Reinforced concrete.	8000
5	Curing	1000
6	Suppling and filling sand	1500
7	Brick masonry	8500
8	Installing fiber glass blank pipe in the borehole including joining with the fiber glass blank pipe/strainer	32000
9	Providing and laying coarse gravels and boulders.	2000
10	Fixing wire mesh	500
11	Miscellaneous items	2000
12	2% Contingencies	1530
13	Repair and maintenance cost	20000
Total		98030
Total cost in USD = 6126.		

4. CONCLUSIONS AND FUTURE DIRECTIONS

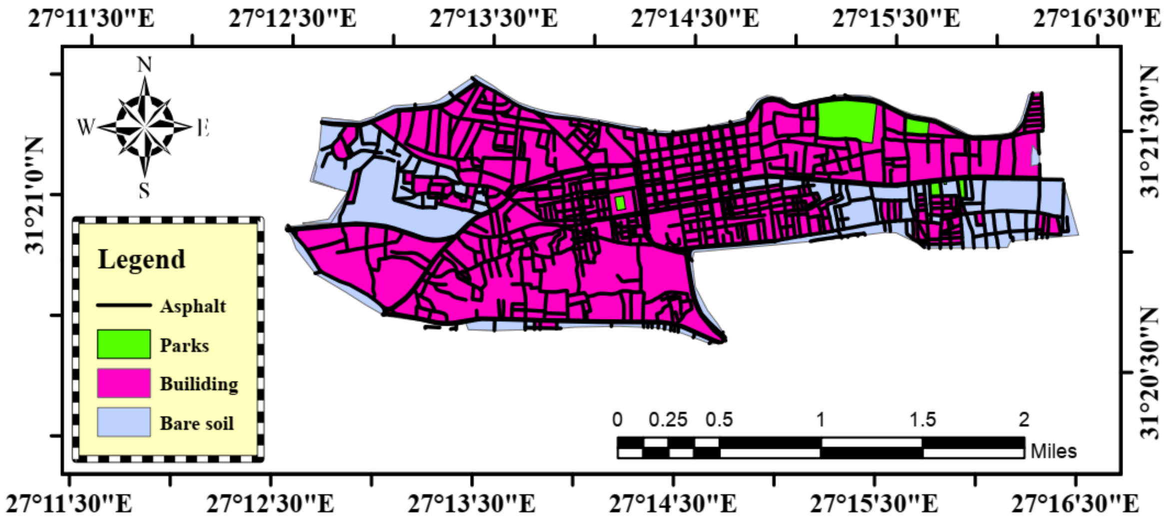
In Egypt, rainfall is mostly occurring on the north coast and decreases inland, and becomes too rare when moving towards Upper Egypt and the western desert. Different techniques are applied for rainwater harvesting and conservation. The proposed design and construction of the recharge wells show a recharge well diameter of 0.45 m, discharge of 25.8 m^3/h in sandy strata of a depth of 20 m from the ground surface, and a permeability coefficient of 25 m/day. As such, RWH can play a significant role to increase water resources especially, on the north coast of Egypt. RWH from Egyptian coastal cities can be used to replace part of the required water from seawater desalination and consequently, the corresponding total costs can minimize. RWH from urban Egyptian coastal cities can share to satisfy the required future water according to the HCWW plan from 2015 to 2037. The rainfall resource represents a small percentage of water resources of Alexandria governorate while it has relatively large percentages in both North Sinai and Marsa Matrouh Governorates. RWH from urban areas in Alexandria city can increase the rainfall share in the Governorate water resources with a percentage of 50%. RWH from urban areas in Marsa Matrouh and Dabaa cities can replace a part of the required water transported from Alexandria and South El-Alamein stations, and consequently, the corresponding total costs can minimize. RWH from urban areas in Marsa Matrouh and Dabaa cities can replace part of the required water from seawater desalination and consequently, the corresponding total costs can minimize. The most economical technique for RWH from urban cities is recharging the rainwater in local aquifers below the cities via recharging wells.

APPENDIX A

(a)

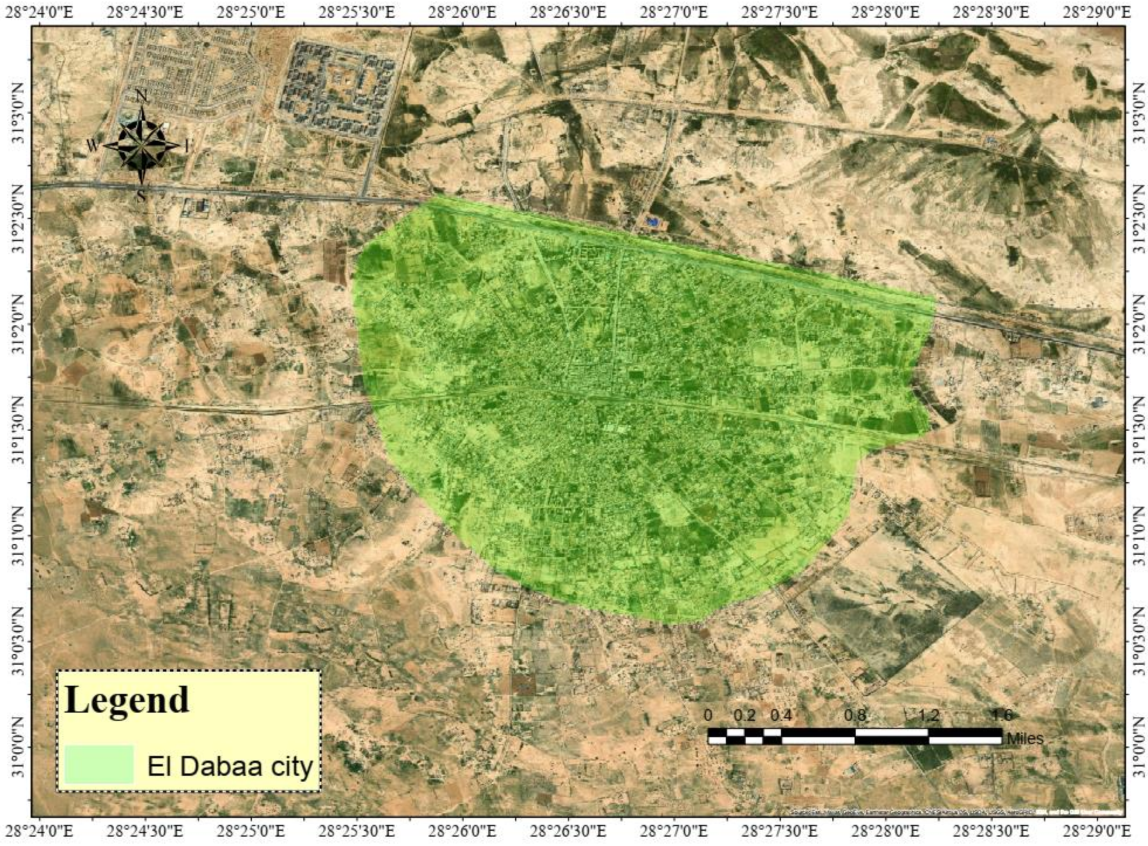


(b)

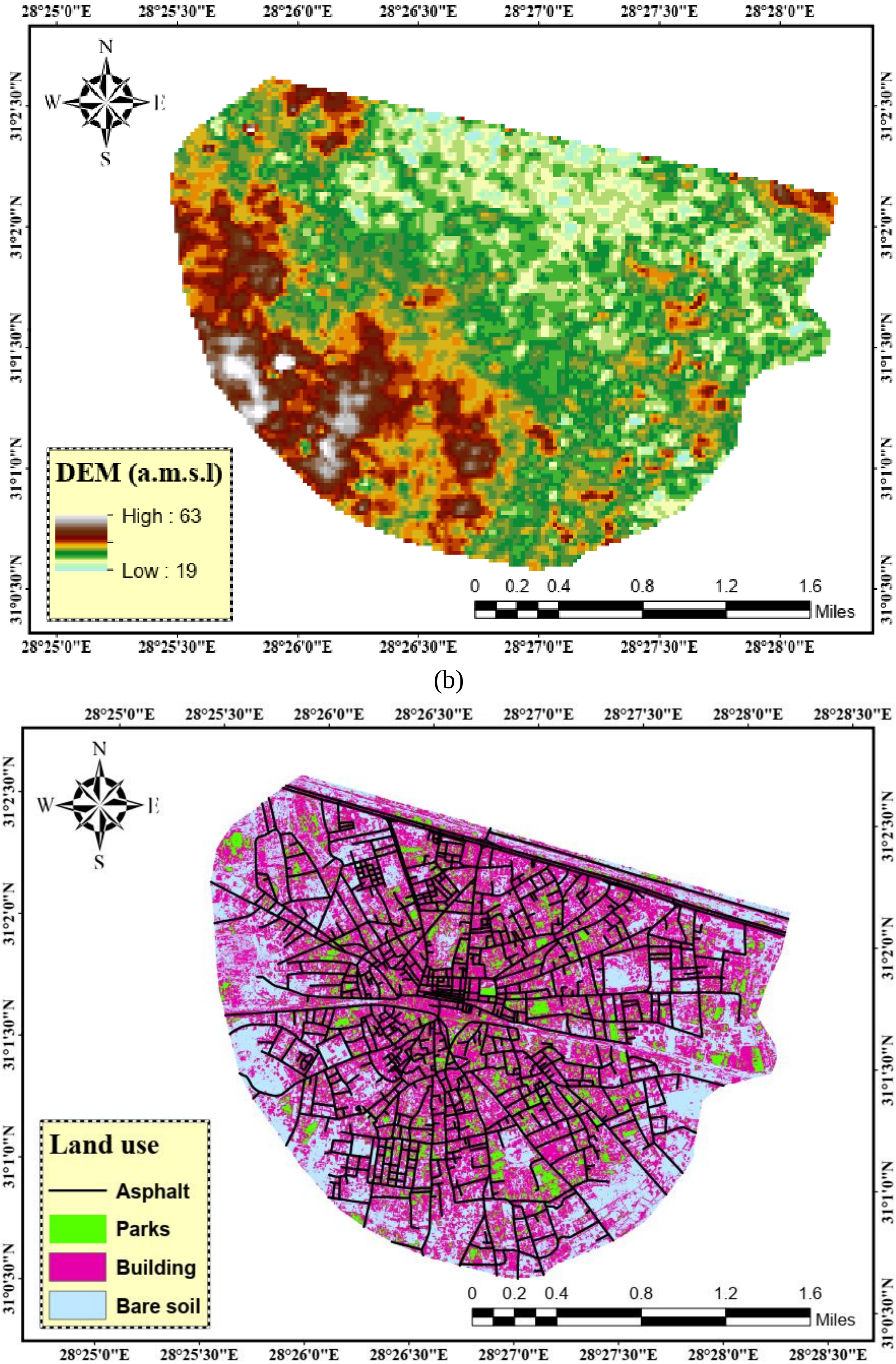


(c)

Figure A1: (a) Google earth map, (b) Digital elevation model, and (c) land use map for the study part of Marsa Matrouh city.



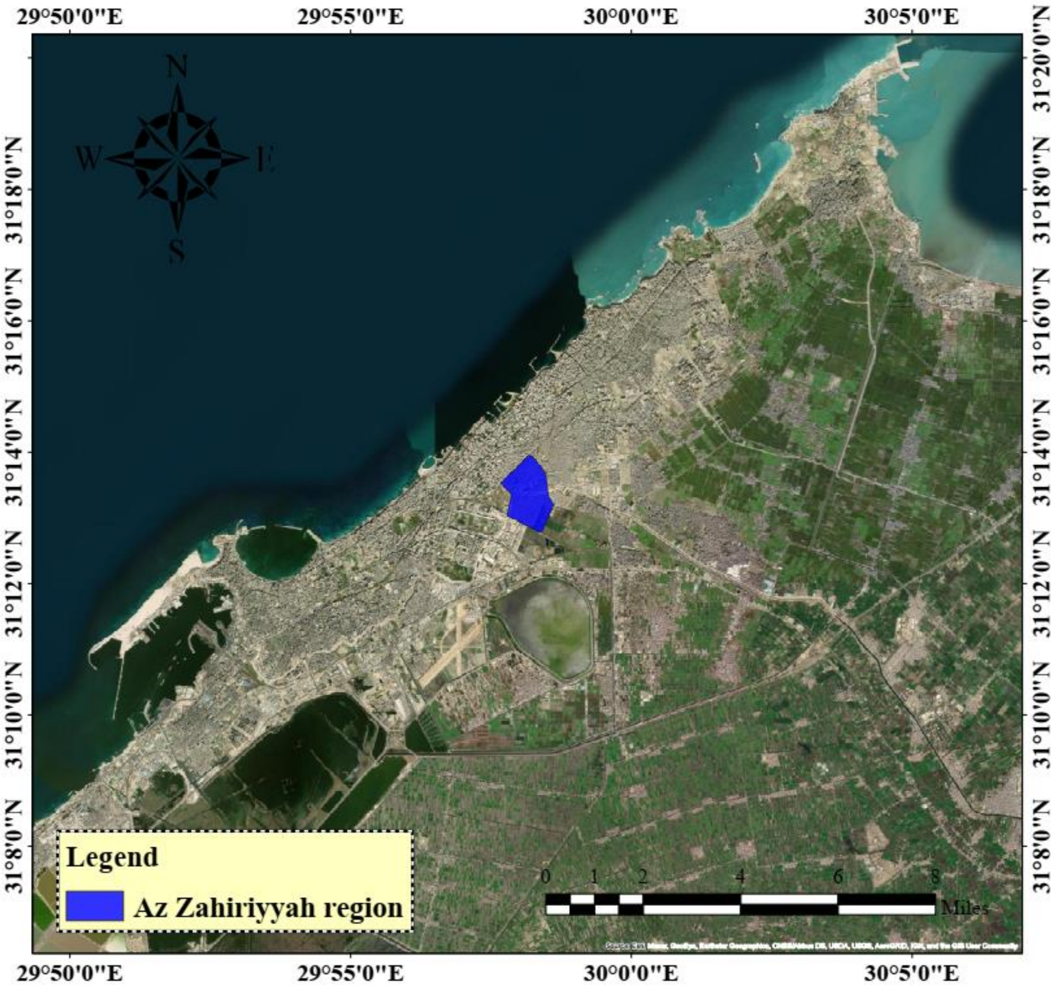
(a)



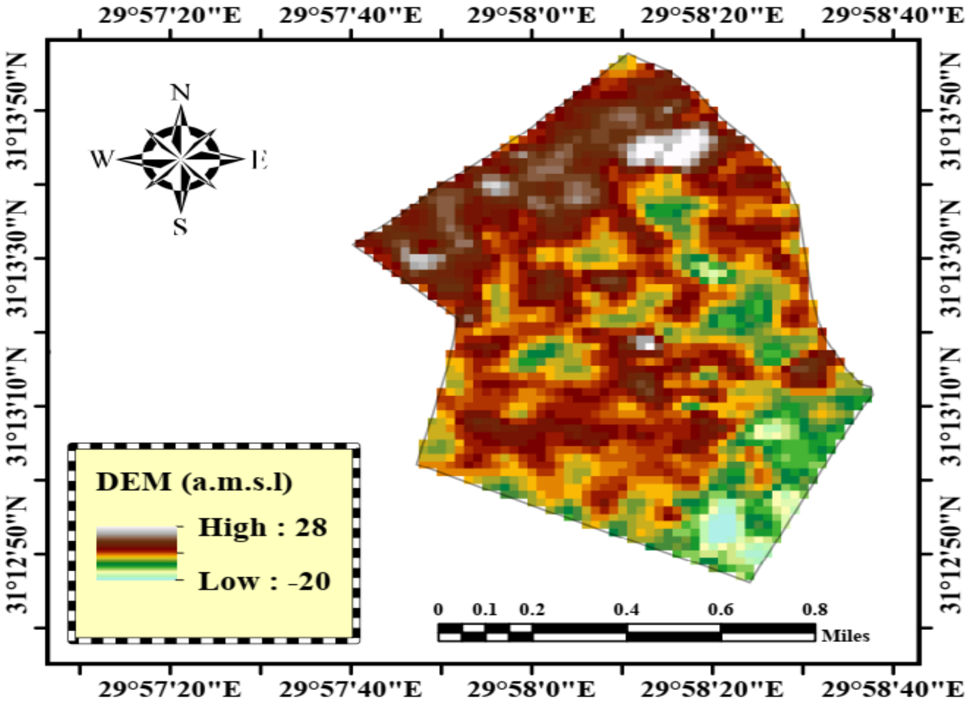
(b)

(c)

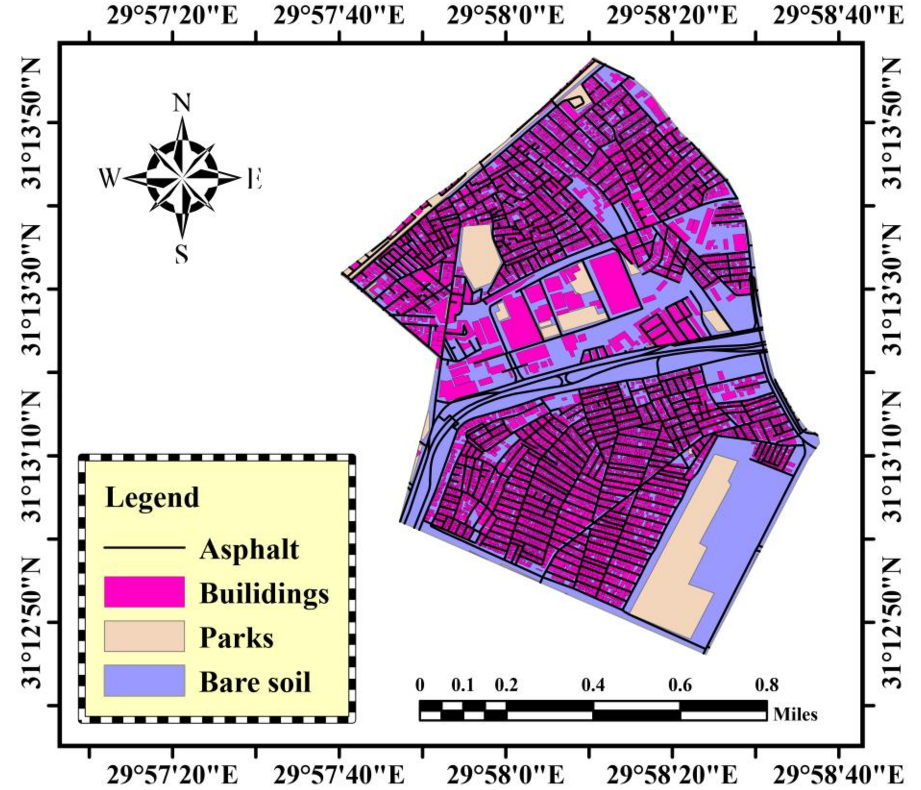
Figure A2: (a) Google earth map, (b) Digital elevation model, and (c) land use map for the study part of Dabaa city.


29°50'0"E
29°55'0"E
30°0'0"E
30°5'0"E
31°20'0"N
31°18'0"N
31°16'0"N
31°14'0"N
31°12'0"N
31°10'0"N
31°8'0"N
N
W
E
S
Legend
Az Zahiriyyah region
0 1 2 4 6 8
Miles

(a)

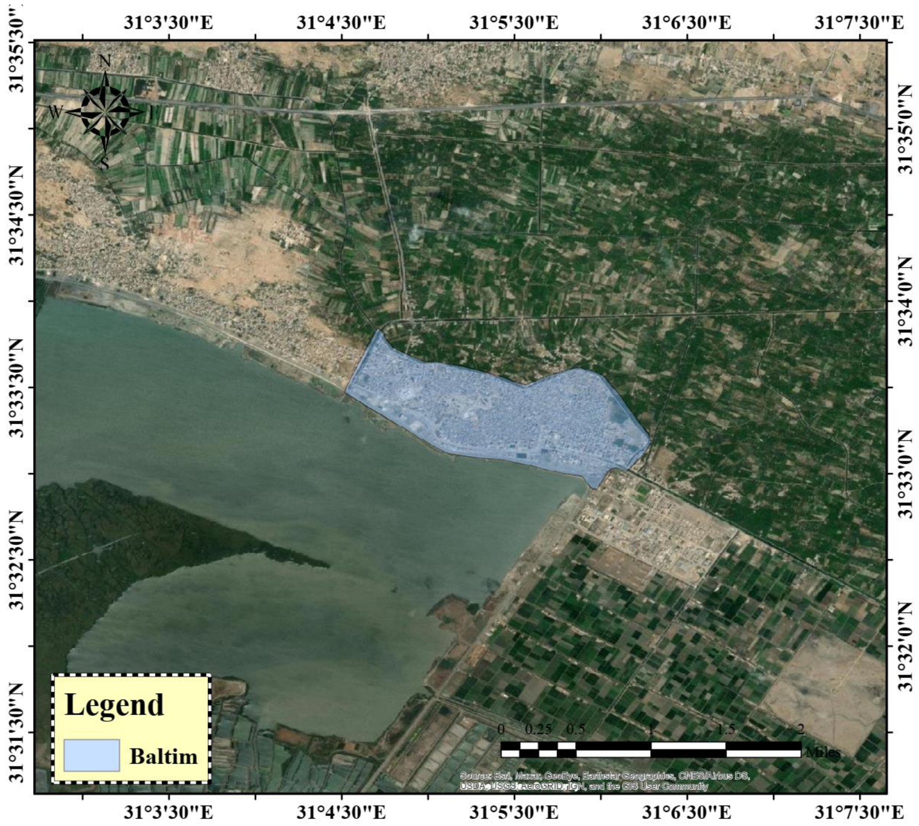

29°57'20"E
29°57'40"E
29°58'0"E
29°58'20"E
29°58'40"E
31°13'50"N
31°13'30"N
31°13'10"N
31°12'50"N
N
W
E
S
DEM (a.m.s.l)
High : 28
Low : -20
0 0.1 0.2 0.4 0.6 0.8
Miles

(b)



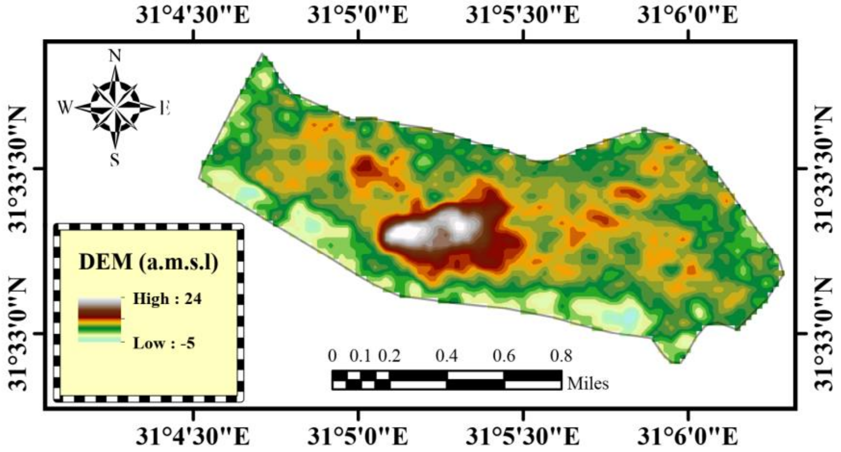
(c)

Figure A3: (a) Google earth map, (b) Digital elevation model, and (c) land use map for Zaheria region in Alexandria city.



Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

(a)



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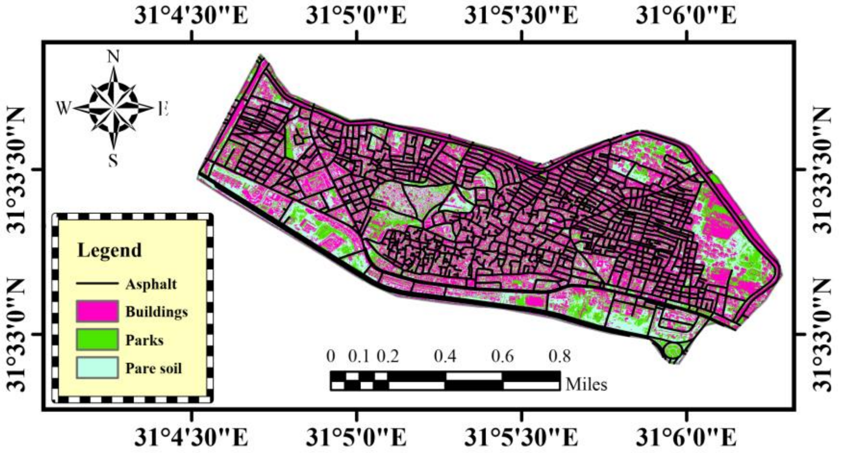
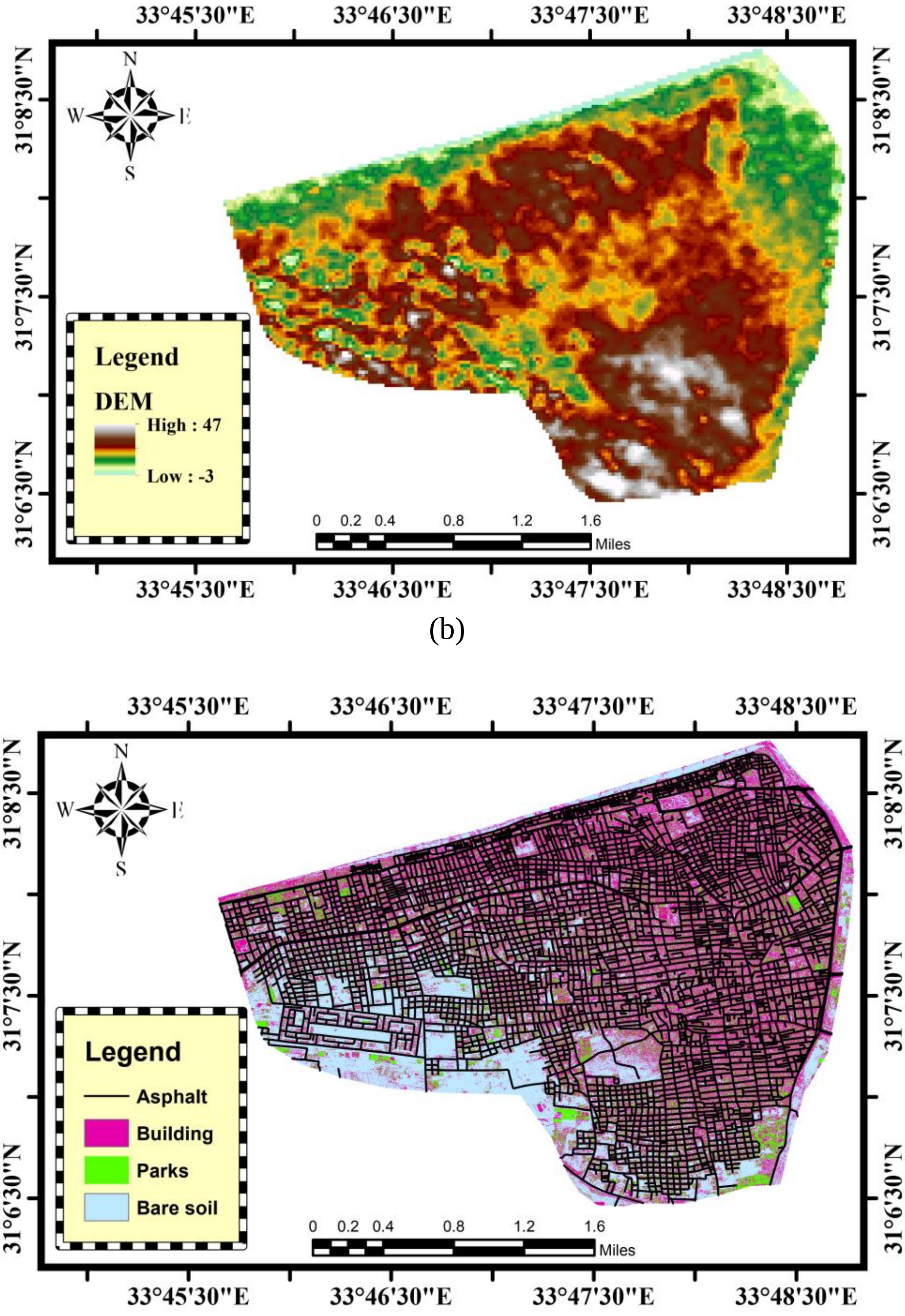


(c)

Figure A4: (a) Google earth map, (b) Digital elevation model, and (c) land use map for the study part of Baltim city.

(a)



(b)

Figure A5: (a) Google earth map, (b) Digital elevation model, and (c) land use map for 1st Department Region in Al-Arish city.

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Credit Authorship Contribution Statement

Mohamed E. Gabr: Methodology, data curation, formal analysis and supervision

Hamdy A. El-Ghandour: conceptualization, software, and formal analysis.

Samer M. Elabd: Formal analysis, review and editing

Declaration of competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Declaration of Funding

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