Recharging the Freshwater Coastal Aquifer of Sidi Kirayr Area Using Sustainable Infiltration Trenches

Medhat M. H. ElZahar* and Mohamed M. M. Amin

Abstract—**Egypt is considered an arid country and depends mainly on the Nile River and groundwater reservoirs to supply water for drinking and various uses. The northwestern coastal zone is one of the regions that rely heavily on groundwater and rainwater for drinking and irrigation. As a result of changes in climate and the rise in sea level, the increase in seawater intrusion is growing. Furthermore, groundwater exploitation and increased pumping of some wells installed in this area have a negative impact on the amount of water in the region's subterranean reservoirs. One of the approaches suggested for managing freshwater lenses floating on top of seawater from saltwater intrusion in this region is to recharge the aquifer lenses with fresh water. This can be done either by injection wells or by use of groundwater mounds, i.e., infiltration trenches. Due to the expected higher cost operation of injection wells, it is interesting to study the recharge of freshwater lenses through the use of groundwater mounds. Studies have been carried out in the past on the Sidi Kirayr area in terms of recording the water table levels and the amount of rainfall before and after the rainy season. However, we propose using an environmentally sustainable economic solution to recharge the underground reservoirs through the use of rainwater instead of letting it run off into the sea. In this respect, an infiltration trench is designed to recharge the aquifer in the Sidi Kirayr area. Two design types for the trench are proposed, with the geometrical calculations of the appropriate dimensions. The trenches are suggested north and south of the asphalt road in the area of Sidi Kirayr, providing that the trenches can be recharged by rainfall or surplus water when being available from other sources.**

Index Terms—**Freshwater lens, groundwater, infiltration trench, recharge, unconfined aquifer**

I. Introduction

When it comes to the water source, we think about lakes, rivers, and streams; in other words, surface water. However, of all of the usable freshwater in the world, approximately 97% is groundwater. In line with the UN, 10 million km^3 of water are stored underground. The U. S. Geological Survey states that there are about 4.2 million km^3 of water within 0.8 km of the earth's surface. Environment Canada cites a study that estimates that each one of the groundwater within the world would cover the surface of the world to a depth of 120 m, while all of the surface freshwaters would only cover the world to a depth of 0.25 m! While groundwater estimates can vary, scientists agree that there's plenty of water under the earth's surface [1].

Groundwater is water that accumulates underground. It can be found in the spaces between loose dirt and rock particles, as well as in cracks and crevices in rocks. Different types of rocks and dirt can hold varying amounts of water. The saturation zone is the area of soil and rock that is saturated with water, whereas the unsaturated zone is the area of soil and rock that is not saturated. The groundwater level is the highest point in the saturated zone.

When it rains, the water infiltrates the soil and percolates downwards until it reaches the groundwater level. Some sorts of soils allow more water to infiltrate than others. Permeable surfaces, like sand and gravel, allow up to 50% of precipitation to enter the soil. Rainwater can take years or perhaps decades to achieve the water level. Thanks to the immense volume of groundwater, once rainwater reaches the geological formation, it often remains there for an especially long period of your time. Some water that's currently stored within the ground could also be rain that fell hundreds or thousands of years ago [1, 2].

Aquifers are underground layers of permeable rock, gravel, sand, or clay that water is extracted. Different kinds of rocks and soils can hold different amounts of water, reckoning on the porous areas (or spaces). When the spaces are large enough to contain usable quantities of water, it's called an aquifer. Large particles, like coarse sand and gravel, can hold more water than fine sand and clay because the spaces between gravel particles are larger than the spaces between fine sand particles. So, we are able to say that gravel features a greater porosity, or ability to hold water, than clay. There are two forms of aquifers: confined and unconfined. All aquifers sit on an impermeable layer of rock or clay. Unconfined aquifers do not have the layer of impermeable clay or bedrock that confined aquifers do. Furthermore, due to the way groundwater is connected to the surface, artesian wells could be drilled into confined aquifers because the high pressure on the water (from the overlying ground) forces the water upwards. During times of drought, unconfined aquifers can recharge nearby streams. Aquifers can range in size from a few hectares to thousands of square kilometers [1–4].

The northwestern coastal zone in Egypt needs innovative ways to conserve water sources due to the distance between the northwestern coastal line and the Nile River. This region depends largely on the use of freshwater by drawing from the upper free aquifers in this region. Climate change and sea-level rise pose a threat to freshwater in the area, exposing it to pollution and saltwater intrusion from the sea. However, attempts are made to use infiltration trenches to recharge the upper fresh unconfined aquifers in the northwestern coastal zone and particularly in the Sidi Kirayr area, which was under study since 1964 [2, 3]. Because of the importance and scarcity of water in the Sidi Kirayr region, the idea for this research arose. Recharging the underground water reservoir in this area conserves rainwater while also preventing

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seawater intrusion into fresh groundwater. As a recharging method for the underground reservoir in the Sidi Kirayr area, a filtration trench was proposed and designed. In addition to the integrated design of the filtration trench, the study demonstrates a novel solution for replenishing a valuable source of groundwater in the Sidi Kirayr area.

II. Literature Review

Recharging coastal aquifers with freshwater from rainfall or other available sources of freshwater and then drawing it back out when necessary is one strategy suggested for managing coastal aquifers. Infiltration trenches can be used to induce the infiltration of water from rain or other available sources into the upper fresh aquifers below. This system is popular when fresh water is beneath saline water, as in the Sidi Kirayr area, where freshwater forms a layer floating on top of saline water. In this case, infiltration trenches are effective in collecting the fresh water and recharging it to the underlying groundwater aquifers. This methodology can be applied in the Sidi Kirayr area for the recharge of its coastal aquifer by infiltration trenches. Abdel-Moogheeth and El-Shazly *et al.* [5] studied the geochemistry of groundwater from the Sidi Kirayr area and stated that the intrusion of salt water from the sea or Mallahet Maryut is responsible for the increased salinity of upper groundwater in the area.

Somaida [6] and Somaida *et al.* [7] state that they looked at the Sidi Kirayr freshwater aquifer's infiltration trench recharge without going into detail about the trenches themselves. Previous studies focused on several problems and parameters related to the recharge of freshwater aquifers. It is important to study all the related parameters, soil types, and physical geology, and find the appropriate solutions to problems when thinking about these sustainable solutions [8–11]. Infiltration trenches are specifically designed and built as surface or subsurface storage areas with permeable bottoms and sides to promote water infiltration into the surrounding soils. As the name implies, the primary mechanism in infiltration systems is the infiltration of stored stormwater into the surrounding soils. Infiltration success will result in groundwater recharge and a reduction in surface runoff [12, 13]. It is important to study the salinity profiles in a freshwater layer stored over saline water in groundwater aquifers before deciding if the location is appropriate for recharging or not [14, 15].

One strategy for managing coastal aquifers is to recharge them with fresh water from rainfall or other available sources of fresh water, then withdraw it when needed [16, 17]. Water from rain or other available sources can be forced into the upper fresh aquifers below using infiltration trenches [18, 19]. As an example, due to overexploitation of the Dar ElSalam coastal aquifer, artificial groundwater recharge was implemented to increase groundwater storage in rainy seasons for use in dry seasons [20].

Current Mediterranean climate trends indicate longer periods of drought and higher temperatures in summer, as well as shorter and more intense precipitation in spring and autumn, necessitating a rethinking of current water management practices [21]. In Italy, Greggio and Giambastiani *et al.* [21] proposed a project called Managed Aquifer Recharge (MAR), which involves redirecting drainage water to infiltration trenches for irrigation and natural infiltration. Although drainage is required to keep the land dry during wet periods, the fresh portion of drainage water could be reused for irrigation or managed aquifer recharge during long periods of stable weather. The proposed Managed Aquifer Recharge project would reroute drainage water to infiltration trenches for irrigation and natural infiltration [21]. In 2011, an analytical study was conducted to answer the question, “Does sea-level rise affect saltwater intrusion?” The answer was that the lifting process would have less influence in unconfined systems due to changes in the value of effective transmissivity. To understand the sensitivity of this self-reversal effect to various aquifer parameters, a detailed sensitivity analysis was also completed [22]. In 2021 a study found that freshwater boundary changes caused by over-pumping hasten saltwater intrusion. Moreover, a recharge pond reduced salinity by 6.26%. In hyper-arid and arid regions, they introduced the TRAD method which can reduce salinity by up to 9.17% [23]. Furthermore, high recovery efficiency is a goal for almost all Aquifer Storage Recovery (ASR) wells, whether they store fresh water in brackish aquifers or fresh aquifers with native water quality constituents that are undesirable in the recovered water [24]. At Hilton Head Island, South Carolina, USA, an ASR demonstration project was built and tested, storing drinking water in a brackish limestone, semi-confined artesian aquifer. The operational performance of this TSV approach for ASR well development has confirmed its viability. The stored drinking water was recovered at an 8 ml/day flow rate for 126 days with an ending chloride concentration of 170 mg/L, achieving 100% recovery efficiency quickly [24].

Multi-criteria decision analysis to identify potential groundwater areas is one of the key types of research when we talk about groundwater, how to access it, and its best use. Some researchers have been successful in accomplishing this using, GIS, analytical hierarchy process (AHP), and remote sensing [25]. The study emphasizes that combining remote sensing and geospatial technology with the AHP technique is an effective tool for regional groundwater management under field data constraints [25].

Sustainable groundwater management through artificial recharge of aquifers has emerged as a potential solution to increasing groundwater depletion and deterioration in several river basins around the world. Aju and Achu *et al.* [26] identifies suitable sites in the Vamanapuram River Basin (VRB), South India, where water scarcity and groundwater declines have caused parts of the basin to fall into the semi-critical category [26]. The study demonstrated the effectiveness of remote sensing and GIS for locating potential zones and locations for various artificial recharge mechanisms in tropical river basins. The findings are very helpful in developing regional plans for sustainable groundwater development and water resource management [26]. Moreover, the locations where underground reservoirs can be used or exploited as a source of fresh water must be identified using potential maps. Therefore, it is always necessary to use cartography to investigate underground water storage facilities, such as those in the Sidi Kirayr region west of the city of Alexandria [27, 28].

III. Freshwater Lenses in Coastal Areas

Due to the difference in densities between fresh and saltwater, a layer of fresh water is formed above the saltwater according to the Ghyben-Herzberg principle. This principle gives the thickness of the freshwater below any point of the water table if the height of the water table above sea level at the same point is known, Fig. 1, and is given by Eq. (1) [8].

$$T = 41\ h \tag{1}$$

where T = thickness of freshwater below a point. h = height of the water table above sea level at the same point.

A. Freshwater Lens Example

The freshwater lens of the Sidi Kirayr area is located 32 km west of Alexandria, a city on the coast of the Mediterranean Sea. The site under investigation in this study covers an area of about 15 km^2 and is bordered by the Mediterranean Sea to the north and Mallahet Maryut to the south, Fig. 2 Sidi Kirayr area had previously been selected as the primary site of the first Egyptian nuclear power plant [5].

1) Definition of Sidi Kirayr freshwater lens

In the Sidi Kirayr area, as in the case of many coastal aquifers, a thin layer of freshwater formed by the percolation of rainwater downward floats on top of saltwater intruded from the Mediterranean Sea.

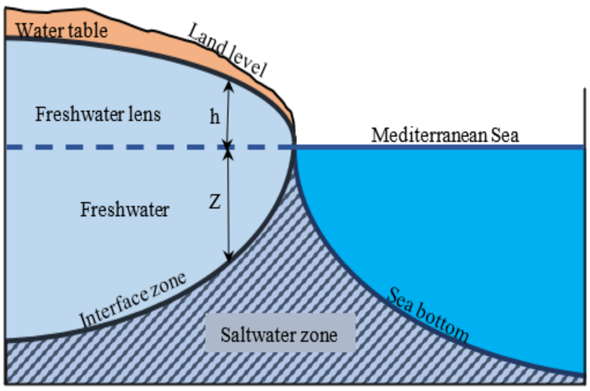


Fig. 1. Cross-section of a coastal area showing the configuration of the fresh-saltwater interface.

The rate of recharge and the volumetric extensions of fresh water are controlled by the local variations in rock permeabilities and topography [9], taking into consideration that, has classified waters in Table I:

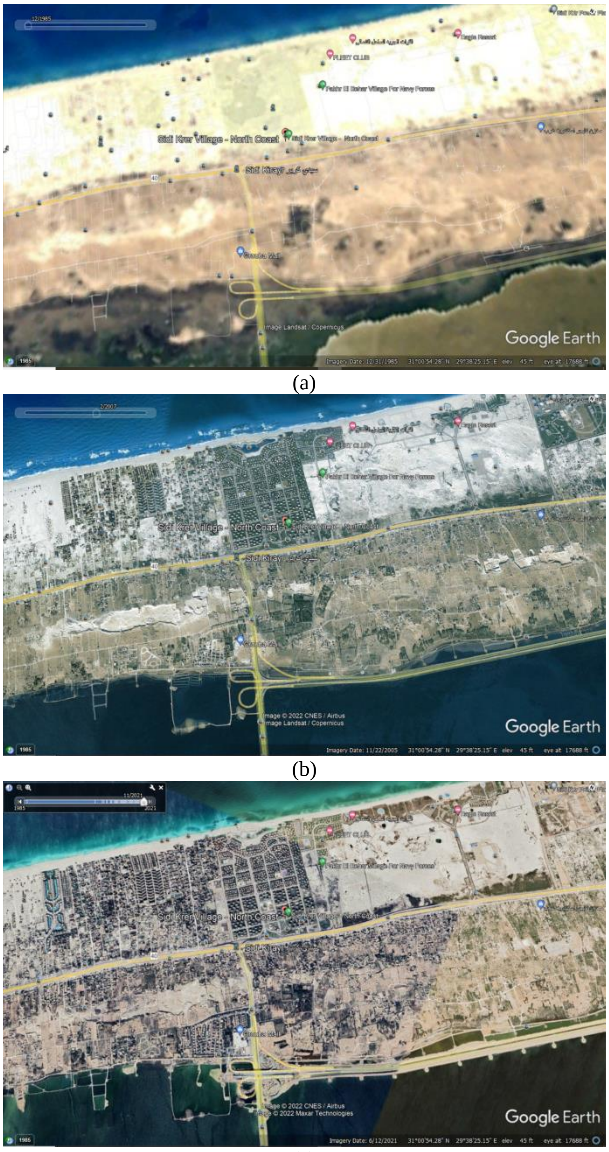
TABLE I: Sidi Kirayr Groundwater Characteristics [9]

Type of water	Salinity (mmhos)	TDS (ppm)
Freshwater	2	1280
Passably freshwater	2–4	1280–2560
Brackish water	4–9	2560–5760
Saltwater	9–50	5760–32000
Extremely saltwater	>50	>32000

2) Geomorphology of the studied area

The geomorphology of the Sidi Kirayr area can be summarized as follows [3–5, 10]:

1) The near-shore ridge (first ridge) is built of semi-consolidated carbonate rocks, reaches about 1 Km in width, and is enclosed by the 10 m height above sea level.
2) The floor of the near-shore depression (first depression) is covered by carbonate sand intermixed with alluvial deposits, with widths ranging from 300 and 700 m, and a ground elevation averaging 5 m above sea level.
3) El Max-Abu Sir ridge (second ridge) is elevated about 25 m above sea level and attains a width of about 200 m. It is built up of detrital limestone.
4) Mallahet Maryut depression (second depression) constitutes the area between the second ridge to the north and Mallahet Maryut Lake. It is affected by lacustrine floats, limestone hillocks, and salty marshes related to Mallahet Maryut.



(a) (b) (c)

Fig. 2. A satellite map for Sidi Kirayr area (a) December 1985, (b) February 2007, and (c) November 2021 [Google Earth maps].

B. Geology of the Studied Area

1) Surface geology

The oolite limestone rocks constitute the majority of the surface bedrock in the study area [2–4]. The rocks belong to the quaternary, including Pleistocene, limestone forming the ridges, and Holocene alluvial (lacustrine and measly deposits) covering the depressions. These rocks are exposed to principally above mean sea level in the subsurface at various depths below sea level.

2) Subsurface geology

The subsurface encountered in the area, interpreted as cored drill holes, could be subdivided into the following rock units from youngest to oldest: loamy deposits, detrital limestone, loose carbonate sand, marl, and massive limestone [8].

1) Detrital limestone: it constituted a great part of the surface bedrock in the area. Locally, the detrital limestone is intercalated by loose carbonate sand lenses of variable thickness. It is noted that the detrital constitutes the upper unconfined aquifer in the coastal strip to the north of Alexandria-Matrouh Road.
2) Loose carbonate sand: it is well pronounced in the northern and southeastern stretch of the area where it attains a maximum thickness of 15 marl pinches down beneath the near-shore depression towards ElMax-Abu Sir ridge. The upper boundary of the aquifer existing in the loose carbonate sand is hidden below the detrital limestone aquifer, with an incomplete hydraulic connection.
3) Massive limestone: it is a fossiliferous origin and underlies the detrital limestone. Also, it is hidden below the younger marl bed beneath the near-shore depression ridge. This rock unit forms the saltwater aquifer in the area, where salinity is above 50 mmhos.

3) Soils in Sidi Kirayr locality

These are differentiated as follows [4, 5]:

a) Soils of the young coastal zone

This zone occupied a narrow strip of land, adjacent to the coastal line. It includes the sandy beach of width 50 m to the south, then followed by the foreshore dunes formed of white oolite sand rising from 5 to 10 m above sea level. Finally, the zone exits the near-shore ridge (first ridge), which is built up of semi-consolidated friable limestone.

b) Soils of the old coastal zone

These are distinguished from north to south as, the new shore depression (first depression), covered with oolite sands intermixed with alluvial deposits from 300–500 m width with an average elevation of 5 m above sea level [3, 4]. The inland ridge (second ridge) of height 25 m above sea level and maximum width of 200 m. It is barren of soil, while its flanks are covered with alluvial soil. Mallahet Maryut depression in soils of calcareous loam, lacustrine flats salty marshes, and Mallahet Maryut lake.

c) Groundwater chemistry

The freshwater lens in the Sidi Kirayr area is of meteoric origin and is bounded to the north by the Mediterranean Sea and to the south by Mallahet Maryut. The chemical analysis of groundwater in the area conducted in [3, 4], of water samples, collected from more than 60 native and drilled wells shows that the total dissolved salts (TDS) range from 500 to 6600 ppm. The lowest values are recorded in the waters beneath the first depression while the highest values are recorded in the portions of the Mallahet Maryut depression. On the other hand, the seawater in the Sidi Kirayr area has a total TDS of 37,700 ppm, while Mallahet Maryut water is characterized by higher salinity of about 57,000 ppm with less homogeneity in chemical composition when compared with seawater [3, 4, 11].

The chemical characteristics of the groundwater have been deeply studied in detail through the analysis of samples collected from 58 dug wells and seven drilled wells. The total results are given in [1]. It is also found that the wells located near the first ridge, when being pumped lead to changes in the water quality. However, the water salinity changes from 1.35 mmhos to 50 mmhos by heavy pumping, caused by the saltwater intrusion of the underlying saline water.

C. Storage Characteristics of the Aquifer

The essential properties of an aquifer are that it must be porous and permeable. However, in the area of the case study, the freshwater lens is included in a carbonate reservoir composed of oolite limestone and carbonate sand. The oolite limestone is now called detrital limestone, which has an average porosity of 37.5% and a coefficient of permeability of 3225 md [3, 4]. On the other hand, the carbonate sand of the studied area is unconsolidated, while its permeability is considerably higher than that of cores. This carbonate sand is related to beach deposits and is in the form of oolite carbonaceous sand [3, 4].

D. Hydraulic Properties of the Aquifer Example

Fig. 3 shows the cumulative curves for carbonate sand, from which the effective diameter d_{10} is found above 0.86 mm. According to Somaida [7], this type of porous material is classified as well-graded coarse sand. He also demonstrated how particle diameters might roughly correspond to pore passage diameters. It is difficult to measure the size of the pore passage. As a result, it has become common practice to relate permeability to grain size. In this respect, the effective size is a good working index of the permeability of the rock because it was found that the permeability of unsorted sand was roughly equal to that of sand compared entirely to the effective size.

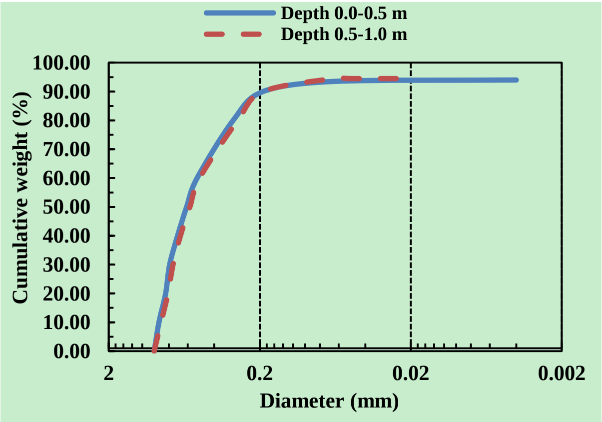


Fig. 3. Cumulative curves for carbonate sand [3].

According to Somaida [7], it was proposed to use the effective size to approximate the hydraulic conductivity as given by the following expression:

$$K_c = 100\, d_{10}^2 \quad (2)$$

where K_c = hydraulic conductivity of carbonate sand (cm/sec) and d_{10} = average effective diameter of carbonate sand (0.086 cm) and K_c = 11.65 m/day, which corresponds to the permeability of 16.3 Darcie's, indicating that the carbonate sand is a highly permeable medium. In the Sidi Kirayr area, the aerated zone and the saturated zone are composed of carbonate sand and detrital limestone, their average porosity and permeability are 40% and 37.7% and 16, 300 md and 3225 md, respectively. They are considered excellent reservoirs for the storage of fresh groundwater.

E. Annual Recharge of the Studied Aquifer

Recharge is the process of adding water to the groundwater reservoir within the Sidi Kirayr area's freshwater aquifer as a result of wintertime rainfall. This water moves from the land's surface to the strata below until it reaches the water table, at which point it is discharged further down the gradient to the Mediterranean Sea in the north and Mallahet Maryut in the south.

The average rate of effective rainfall in the area has been calculated at 157 mm; however, a small amount of this quantity 26 mm reaches the water table, while the remainder is lost through evaporation, evapotranspiration, and overland runoff [7, 8].

IV. Recharge of Sidi Kirayr Coastal Aquifer

Water discharged into a so-called dry well, surface pond, settling basin, or pit trench may ultimately enter a fresh groundwater aquifer following percolation through the aeration zone. The zone of aeration consists of the unsaturated material above the water table in which the pore spaces and interstices between the rock particles. A dry trench that is finished above the water table in the aerated zone can be used to collect water from runoff during rainfall. In general, the movement is downward, although the free water is dispersed laterally by capillarity. The water enters the upper part of the aquifer, as shown in Fig. 4. The distance, direction, and velocity of underflow are affected by the hydraulic gradient and the rate of groundwater movement in the aquifer.

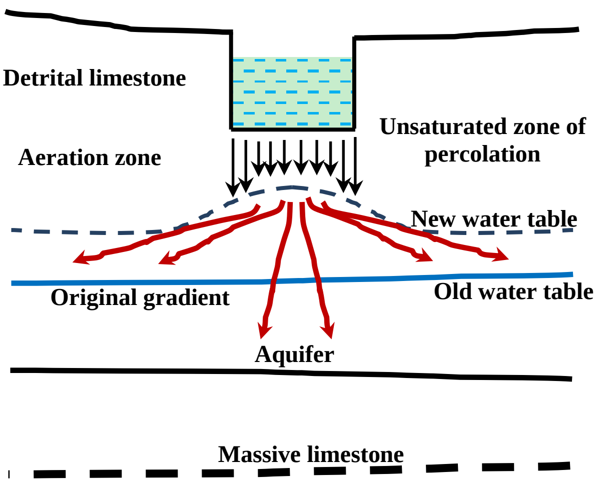


Fig. 4. Diagram showing percolation of recharged water through the aeration zone into a water table aquifer.

A. Recharge Areas in Sidi Kirayr Locality

The maximum water heights in the Sidi Kirayr area above sea level is relatively low, on average being 0.73 m before the rainy season and 1.04 m after it [3, 4]. These levels are usually existing adjacent to the middle part of the asphalt road. However, it is concluded that the best areas for recharge of the freshwater aquifer existing in the locality are; first, an area located north of the asphalt road and extending to the Mediterranean Sea coastal line; and second, an area located south of the asphalt road to Mallahet Maryut. These are shown in Fig. 5 which reproduces a topographic map constructed for the Sidi Kirayr locality from [3, 4].

B. Design of the Infiltration Trench

Infiltration trenches are shallow trenches with a coarse stone aggregate underground reservoir. The aggregate-created void stores surface runoff that has been diverted into the trench. This runoff then percolates into the surrounding soil via the trench's bottom and sides. Infiltration trenches are primarily used to improve water quality; however, when equipped with underground piping, the trench's temporary storage volume can be increased to provide peak runoff rate reduction for one- and two-year return frequency storms. Peak rate control of 10-year and larger storm events is typically beyond an infiltration practice's capabilities [12].

C. Constraints and Design Criteria

When proposing an infiltration trench, the following constraints and design criteria should be considered, according to [12]:

1) To provide a safety factor and account for performance decline as the facility ages, the soil infiltration rate upon which a trench design is based should be one-half the infiltration rate obtained from the geotechnical analysis.
2) Following a runoff-producing event, infiltration trenches should be designed to empty within 48 h.
3) There is no restriction on the minimum drainage area. The maximum drainage area, however, should not exceed 20,000 m^2. To collect runoff from larger drainage areas, multiple trenches may be used. These trenches are appropriate for on-site slopes of less than 20%.
4) The total depth of the trench ranges from 0.6 to 3.0 m. The trench surface area is the area that, when multiplied by the trench depth and aggregate porosity, yields the computed treatment volume. Trench widths should be no more than 2.5–3.0 m.
5) The infiltration trench material should be clean aggregate with a diameter ranging from 3 to 9 cm. This specification calls for open-graded coarse aggregate or its equivalent. At the bottom of the trench, a 20 cm deep sand layer must be installed. This material must have a fine aggregate.
6) An observation well is recommended every 15–20 m along the length of the trench. Observation wells are useful for monitoring dewatering times to ensure that the trench empties within the maximum allowable time of 48 h. The observation well is typically made of 100 to 150 mm perforated PVC pipe.
7) The trench aggregate material should be surrounded by filter fabric that is not placed on the trench bottom.
8) In loamy soils, acceptable soil infiltration rates for these trenches range between 0.31 and 5.28 m/day.
9) A distance of at least 0.6 m between the bottom of an infiltration trench and the surface of the seasonally high-water table is required. The assumed separation distance should allow the trench to empty within 48 h of a runoff event.

10) Infiltration trenches should be at least 6 m downslope and 30 m upslope from the building foundations. Trenches should also not be built within 30 meters of any water supply well.

In the Sidi Kirayr area, the losses of fresh groundwater are mainly caused by the exploitation of water for domestic and irrigation purposes from wells, as shown in Fig. 5, subsurface flow to the sea, Mallahet Maryut, and evapotranspiration. [10–12].

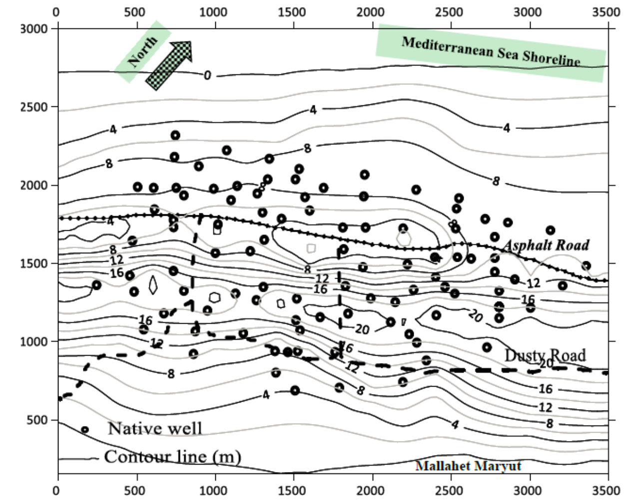


Fig. 5. Index map of Sidi Kirayr area showing the distribution of t*he native wells (reproduced from [6], [7]).

D. Design of Infiltration Trench

The following type of infiltration trenches, see Fig. 6, can be used in areas where construction and development have not taken place. This is done before planning and implementing utility networks to take full advantage of rainwater in refilling underground reservoirs [12].

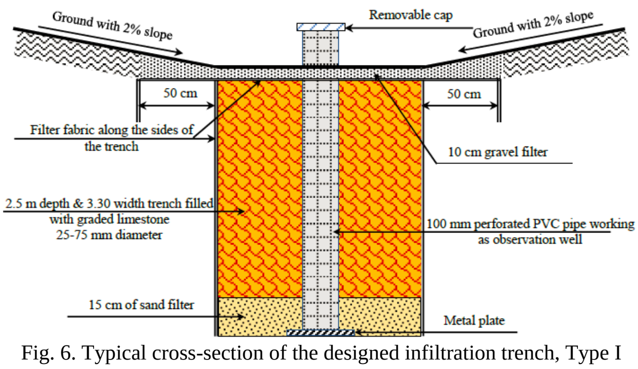


Fig. 6. Typical cross-section of the designed infiltration trench, Type I (Not to scale).

The following steps can be used to design the required infiltration trench:

The water volume can be computed as follows:

$$WV = A_I \times H_{ra} \quad (3)$$

where WV = the water volume from average rainfall, A_I = The watered area = $\pi * (1500)^2$ = 7,071,428.6 m^2 (The studied area is about 3 × 3.5 km)

H_{ra} = average rainfall intensity = 26 mm [5].

$$WV = 7{,}071{,}428.6 \times 0.026 = 183{,}857 \text{ m}^3$$

Considering a factor of safety of 50%, then the design water flowing volume = 183,857 × 1.5 = 275,785 m^3

The trench depth is given by:

$$d_{trench} = \frac{I_r \times T_d}{v_r} \quad (4)$$

where d_{trench} = maximum trench depth, I_r = design infiltration rate, T_d = maximum allowable drain time, should not exceed 48 h, taken 24 h [12, 16, 18], and V_r = void ratio of the used stone, 0.4 for coarse graded aggregate.

Taking, the average infiltration rate ranges from 0.1 to 1.0 m/day for loamy soil [10, 13], taken 1.0 m/day.

As a factor of safety as well as to avoid the decline in performance with time, It is taken 0.5 of the infiltration rates of the native soil, then:

$$d_{trench} = \frac{0.5 \times 1.0 \times 48}{24 \times 0.4} = 2.5 \text{ m}$$

The minimum allowable trench bottom area:

$$SA_{trench} = \frac{WV}{I_r \times T_d} \quad (5)$$

where SA_{trench} = minimum trench bottom surface area (m^2), WV = treated water volume (m^3), I_r = design infiltration rate, and T_d = maximum allowable drain time (48 h)

then,

$$SA_{trench} = \frac{275785}{0.5 \times 1.0 \times 48} = 11491 \text{ m}^2$$

Assuming the width of the infiltration trench = 3.30 m, then the total length of the trench is equal to about 3500 m.

Considering the use of a perforated pipe(s) within the trench, see Fig. 7, can increase the storage capacity and reduces the overall dimensions of the trench. This can be used to reduce the overall dimensions of the trench, and/or, have the same trench size fixed and provide a greater overall volume of infiltration.

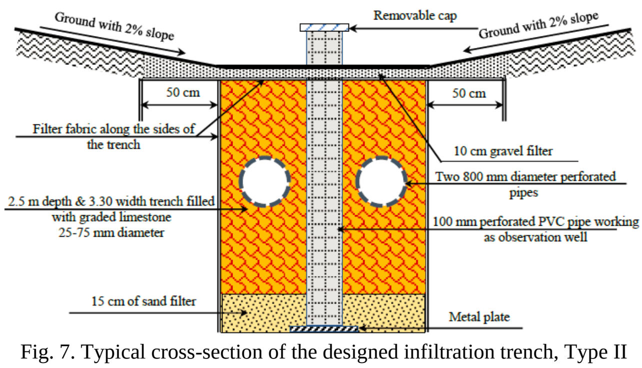


Fig. 7. Typical cross-section of the designed infiltration trench, Type II (Not to scale).

The following steps illustrate the procedure for the redesign of the trench to decrease the depth by providing perforated pipes within the trench [12, 19]. This design method can also be adapted to resize the trench length and/or depth.

In this example, an 800 mm perforated metal pipe will be placed within the trench. Assuming the pipe extends the full length of the trench, thus:

$$V_{pipe} = L \times \pi \times r^2 \times N$$

where $\mathbf{V_{pipe}}$ = the total volume provided by the pipe, r = the radius of the pipe (0.4 m), N = the number of the pipes, take 2, L = the total length of the trench (3500 m)

$$V_{pipe} = 3500 \times \pi \times (0.4)^2 \times 2 = 3520 \text{ m}^3$$

The volume of limestone to be replaced by the pipe is computed as follows:

$$V_{net} = 3520 - 1408 = 2112 \text{ m}^3$$

Thus, the net increase in storage by using the pipes instead of the limestone equals 2112 m^3

Therefore, the trench depth can be reduced as follows:

$$d_{reduced} = \frac{2112}{3520 \times 3.30 \times 0.4} = 0.5 \text{ m.}$$

The depth of the modified trench is as follows:

$$d = 2.5 - 0.5 = 2.0 \text{ m, but it can be taken as 2.5 m.}$$

The volume provided by the modified trench is as follows:

$$V_{trench} = 3500 \times 3.30 \times 2.5 \times 0.4 = 11550 \text{ m}^3$$

Thus, adding the two 800 mm perforated pipes provided a total volume = 11550 + 2112 = 13662 m^3.

V. Locations for Designed Artificial Trenches

The designed trenches can be used in locations as where there has been construction and development, as well as road construction. This is accomplished by selecting the most appropriate locations adjacent to the asphalt road. In this case, the designed trench can be distributed in the Sidi Kirayr area north of the asphalt road. The parts of the trench can be located over different zones and carefully selected in the locations with most of the levels 8 m, see Fig. 8.

This choice is important to utilize full use of rainwater in recharge of the underground reservoirs and thus solving the problem of seawater intrusion. Moreover, this idea can avoid the severe impact of the pollution problem of the aquifer water, thus avoiding the withdrawal of water with increased salinity. It is suggested to use the two types of trenches (Type I or Type II) (Fig. 6 and Fig.7), depending on the total targeted cost.

On the other hand, the area south of the asphalt road is not fully occupied by buildings, so, it is suggested to use full-length infiltration trenches (Type I or Type II), which are located in the second depression with levels ranging from 4 to 12 m, see Fig. 8, recharging the freshwater aquifer towards Mallahet Maryut.

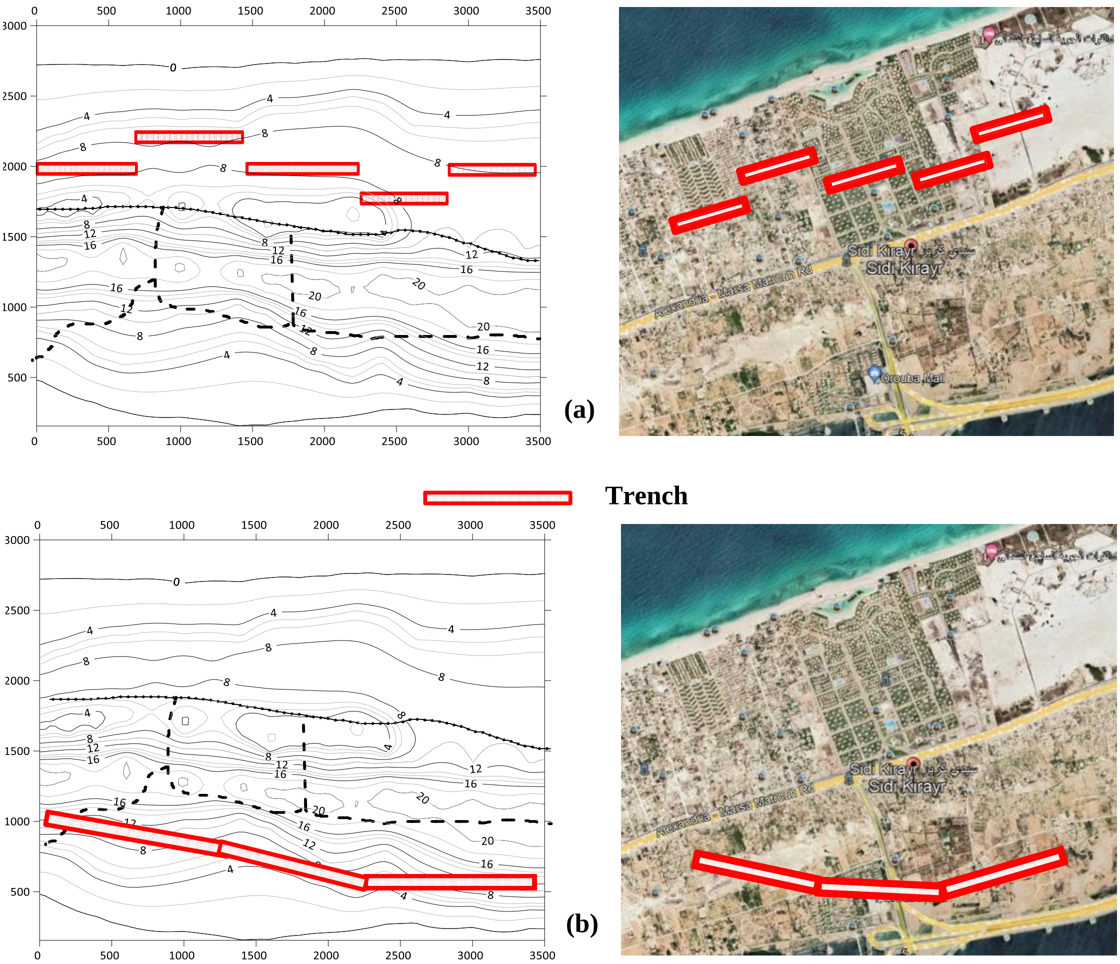


Fig. 8. A map showing the site and proposed locations of the designed trenches recharging the groundwater aquifer of the Sidi Kirayr area. (a) North of the asphalt road (discontinuous); (b) South of the asphalt road (continuous)

Finally, the suggested solutions result in the recharge of the groundwater aquifer during the rainy season, protecting the aquifer from being affected by saltwater intrusion from the sea and Mallahet Maryut, which is increasing with time as a direct result of global warming and climate changes. When any of the proposed infiltration trenches is recharged from rainfall or surplus water, a groundwater mound is built up, creating a gradient, and water moves in various directions through the natural gradient of the upper aquifer's water table, as shown in Fig. 9. In such case, the degree of built up of the mound, and hence, the distance the water moves opposite to the natural gradient is controlled by the slope of the hydraulic gradient, the physical character of the aquifer and the quantity of recharged water.

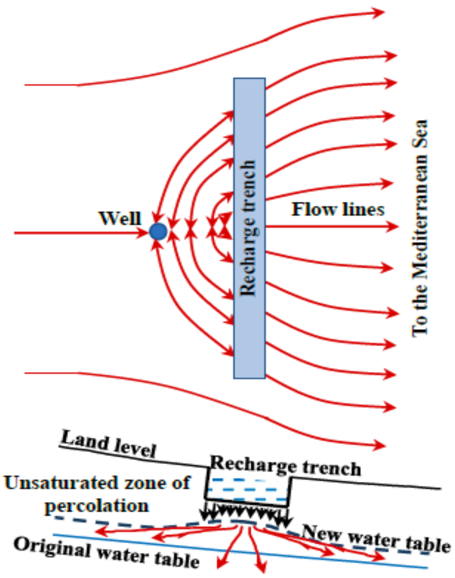


Fig. 9. Diagram showing expected lines of flow from a recharge mound on the original water table in the north part of the Sidi Kirayr area.

VI. Conclusion

The conclusions obtained through the present study can be summarized as follows:

1) The study area occupies a portion of the undulated coastal plain in Egypt which stretches close to the Mediterranean Sea coastal line, 32 km west of the city of Alexandria. Two coastal zones could be distinguished in the Sidi Kirayr area: a young coastal zone including a sandy beach, and foreshore sand dunes as the first depression, and the old coastal zone including the first depression, the first ridge, and the second depression. Moreover, the Sidi Kirayr area is geologically constructed of a succession of late tertiary quaternary rock units. The rocks of the quaternary age include detrital oolite limestone and massive limestone. In the Sidi Kirayr area, detrital limestone forms an upper aquifer, while massive limestone constitutes the underlying salt water from the Mediterranean Sea.
2) In the Sidi Kirayr locality, recharge of its coastal unconfined aquifer can be accomplished using infiltration trenches. This trench will fill the groundwater aquifer during the rainy season inexpensively due to the abundance of limestone exposures in the northwestern coastal zone and the Sidi Kirayr area.
3) Recharge to the aquifer will be carried out in carbonate sand and detrital limestone. The first has a porosity of 40% and a permeability of 16,300 md, while the latter has a porosity of 0.375 and a permeability of 3225 md. This means that the aquifer has a good ability to store and yield fresh groundwater. The recharged water to the aquifer may flow at a low velocity from the trench to displace and compress the original water in the aquifer.
4) The infiltration trench is designed with two proposals (I, II) through which one can be chosen for use in the area north of the asphalt road as well as the area south of it. In this view, the basic dimensions of trenches (Type I, and Type II) are designed and located in the aforementioned areas. It is noted that the sites of the trenches should be chosen to be laid in areas with low levels, north of the asphalt road and in the south part. Their levels range from 4 to 12 m.
5) Such artificial recharge of the aquifer is advantageous for several purposes: storage of rainwater; displacement of saline water, particularly in the areas threatened by saltwater intrusion; and recovery of water levels in the aquifer if it is subjected to significant declines of the head because of heavy exploitation of water from native wells and pumping.

Nomenclature

T = thickness of freshwater in freshwater lens below a point.

h = height of the water table above sea level at the same point.

WV = water volume from average rainfall.

A_I = basin area.

H_{ra} = average rainfall intensity.

d_{trench} = maximum trench depth.

I_r = design infiltration rate.

T_d = maximum allowable drain time.

V_r = void ratio of the stone used.

SA_{trench} = minimum trench bottom surface area.

V_{pipe} = total volume provided by the pipe used.

L = total length of the trench.

r = radius of the pipe.

N = the number of pipes used.

d = depth of the modified trench.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

MMHE, co-developed the research idea, designed the recharge system, and discussed and corresponded with the Journal, MMMA collected the field data, co-wrote the basic version of the paper; and supervised the research. The two authors approved the final version.

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