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Assessment of Stormwater Infiltration Basins Models Developed in Gaza Strip

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Abstract—Stormwater remains the sole source of aquifer recharge in the Gaza strip, which should be utilized properly through artificial infiltration. The study objective is to investigate and analyze the infiltration efficiency of three large exiting infiltration basins in the Gaza strip (Alamal, Asadaqa, and Waqf) using different infiltration techniques. The technique applied in Alamal basin is the natural surface spreading of stormwater while Asadaqa basin used the surface spreading combined with graveled boreholes. Waqf basin used non-graveled boreholes (empty shafts cased with UPVC pipes). The infiltration rate and efficiency were recorded and estimated for each basin during the 2021-2022 wet season and compared to a past 2017-2018 wet season at a water depth of 1.70 m.

The study revealed that, the actual infiltration capacity of Waqf basin was estimated as 2,000 m^3/day in the 2021-2022 wet season, twice that in the 2017-2018 wet season, with an infiltration efficiency of 57.47 %, that was attributed to the 18 drilled non-graveled boreholes, which enhanced the seepage of stormwater into the underlying soil. Asadaqa basin has the lowest infiltration efficiency of 3.90 % due to the continuous accumulation of thick and dense sediment layer on the basin floor, with nonchanged actual infiltration capacity (around 2,800 m^3/day) between the two studied wet seasons. On the other hand, Alamal basin infiltration efficiency was only 4.60 %, with actual infiltration capacity of 629 and 105.4 m^3/day during the two wet seasons, respectively where some repair and upgrade works were performed at Alamal basin which enhanced the actual infiltration capacity but still far from the design infiltration capacity. For future studies, Waqf basin technique should be thoroughly studied and investigated as a novel artificial infiltration method, with deep study on the factors affecting the infiltration process.

Index Terms— Stormwater, Infiltration Basin, Drywell, Water Depth, Clogging, Aquifer.

I. INTRODUCTION

Groundwater is considered the only source of freshwater supply in the Gaza strip used, for domestic, agricultural, and industrial purposes, and the main replenishment source for the Gaza coastal aquifer through infiltration. Other infiltrating components are available, for instance, water irrigation activities, wastewater and domestic water leakage from networks, retention and sedimentation ponds, cesspits, and soak ways. The recharging components are directly influenced by human activities, which in many cases discharge substandard water quality that infiltrate into the soil and percolate to the groundwater resulting in unrecoverable contamination of groundwater quality. In some areas, the over-extraction of groundwater has led to a continuous lowering of the groundwater table up to 10 m below the mean sea level [1]. This has a detrimental effect on the aquifer allowing for seawater intrusion, which led to a significant and irreversible deterioration in groundwater quality.

Furthermore, the high population growth rate is exacerbating water scarcity in the Gaza strip, with continuously decreasing rates of stormwater infiltration due to rapid urbanization activities, expansion of built-up areas, and global climate change. Amid all mentioned constraints and complications affecting water situation in the Gaza Strip, the importance of enhancing stormwater infiltration into the Gaza coastal aquifer is increasing with time. Thus, understanding the artificial recharging systems and studying the applied engineering technologies is very important and will assist in alleviating the Gaza water deficit and the deterioration of groundwater quality and quantity [2]. The volume of stormwater infiltrating into underlying ground formation depends upon a large number of affecting factors: soil characteristics, land use, land cover, soil saturation, temperature, water table, water composition and other variables.

Infiltration phenomena is a very complex process studied by many previous researchers trying to precisely describe the behavior of water when invading soil pores to replace entrapped air within a complicated microscale processes that influence a macroscale general behavior of infiltration process. Numerous methods and approaches were created to estimate infiltration rate such as: in situ measurement method, which is commonly known as field observed measurement data-driven approach, where this approach was applied in this study.

Empirical models such as Green-Ampt, Kostiakov, Horton, Philip, Holtan, and others were generated to estimate cumulative infiltration and infiltration rate, some are accurate to a certain limit that can give satisfactory results, others are not and can be only applied under specific assumptions.

Darcy (1856), a French engineer who performed several field experiments on the behavior of water infiltration and he formulated the first best known empirical equation for describing the water flow through saturated porous media, known as Darcy's law expressed in Equation 1 [3].
The equation opened a new conceptualization for infiltration process that widened the researchers and scientists' scope of thinking for further studies and investigations.

$$f = -K_s \frac{\Delta\Phi}{L} \tag{1}$$

where f is water flux in (length/time) flowing through unit sectional area in unit time. K_s is saturated hydraulic conductivity and $\Delta\Phi$ is the difference between two points of different hydraulic head separated by a distance L. Darcy's law is valid for laminar flows of specific Reynolds number smaller than 1.0 [4]. However, Forchheimer in 1930 proposed a correction for Darcy's law at Reynolds number larger than 1.0.

Another famous equation was proposed in 1931 by Richard, which was formulated to describe unsaturated flow as a continuity of Buckingham study on extending Darcy's law [5]. Richard's equation can be used for 3-dimensional unsaturated flow with a complicated form of equation, yet the widely used is 1-dimentional expression for the vertical infiltration as expressed in Equation 2.

$$\frac{\partial\theta}{\partial t} = \frac{\partial\theta}{\partial z}\left[K(\varphi)\left(\frac{\partial\varphi}{\partial z}+1\right)\right] \tag{2}$$

Where z is vertical distance, K is saturated hydraulic conductivity, φ is capillary suction and θ is moisture content, thus saturated hydraulic conductivity was replaced with a function of soil moisture content.

Kostiakov [6] and Horton [7,8] are considered to be the best known empirical equations used to present infiltration rate. The proposed equations have critical limitations that may hinder their application. Since they depend on complicated parameters that cannot be readily estimated from the available soil information. Kostiakov empirical model is expressed in Equation 3 [6].

$$f(t) = \alpha(t)^{-\beta} \tag{3}$$

Where f is infiltration rate at time t; α and β are empirical constants, the model well describes infiltration rate within small time duration but less accurate at larger time duration.

Horton also proposed a famous and well known equation in 1940 as given in Equation 4, to describe the basic behavior of infiltrating water, however the decay constant was difficult to obtain and poorly defined, that was one of main drawback of the model [7,8].

$$f(t) = f_f + (f_o - f_f)e^{\gamma t} \tag{4}$$

Where f_f and f_o are final and initial infiltration rates respectively, t is the time since rainfall start and γ is an empirical constant.

Other important empirical models and mathematical equations of infiltration process were expressed by Philip [9] and Green-Ampt [10], both of which used parameters and information that can be obtained from soil data, particularly that of Green- Ampt model. In addition, Fok [11] summarized in his study the development and limitations of using various infiltration models. Massmann [12] provided a design manual for sizing infiltration basins by developing Green-Ampt model.

In this study, the actual infiltration rate, capacity, and efficiency were estimated by in situ observation approach for three existing basins in the Gaza strip (Waqf, Asadaqa, and Alamal) that uses different infiltration techniques.

II. STUDY AREA

1. Alamal Basin

Alamal infiltration basin is located in the west of Khanyounes city (Latitude 31°21'38.79"N and longitude 34°18'2.52"E). The catchment area is 10 km^2 with an amount of 89,215.0 m^3/hr as a surface runoff flowing into the basin during rainy seasons [13].

The catchment area collects stormwater through a box culvert that conveys the stormwater into the basin for retention until seeping gradually into the underlying groundwater over time, see Figure 1.

Figure 1: Layout of Alamal infiltration basin (Google map, 2022)

Alamal basin used the direct surface spreading of stormwater without augmenting drywells (infiltration boreholes). Based on [13], with a hydraulic conductivity $k = 6.67$ m/day and a hydraulic gradient $i = 0.134$, the design infiltration rate of Alamal basin was estimated as 0.8041 m/day using Darcy's law. Furthermore, multiplying the design infiltration rate by the basin floor area of 17000 m^2, we get the design infiltration capacity of 13,670 m^3/day.

The soil profile beneath the bottom of Alamal basin was very heterogeneous with relatively impermeable clay layers extending below the water table. Based on the results of previous soil investigation, there are thick layers of sand that extend to the water table and are overlaid by lenses of clay layers that reduce soil permeability.

2. Asadaqa Basin

Asadaqa infiltration basin is located in Atuffah district of northeastern Gaza City (Latitude 31°30'43.99"N and Longitude 34°28'32.87"E). The basin location was best suited to collect the surface runoff created from stormwater. Since the basin is at the lowest elevation, it contributes significantly to intercepting the stormwater from the surrounding areas. The catchment area is 2.5 km^2 [14]. Asadaqa basin was designed using a combination of two techniques; the surface spreading and the vadose-zone wells (graveled drywells) which did not reach the groundwater table. The basin consists of two main sub basins; the northern and southern basins, see Figure 2. The basin floor area was estimated as 8,000 m^2.

Figure 2: Layout of Asadaqa infiltration basin [14]

According to [14], a total of 293 boreholes were drilled to enhance the surface infiltration, each borehole has a diameter of 80 cm and was constructed 5 m away from the neighboring borehole in two directions. The borehole was 15 m deep in the ground with 5 m penetration of the Kurkar layer, each borehole was filled with gravel of 10-20 mm size, with an infiltration capacity of 246 m^3/day for each borehole. Thus, the design infiltration capacity of the basin was estimated as 72,078 m^3/day by multiplying the number of drywells (293 boreholes) by the design infiltration capacity of each borehole (246 m^3/day).

Regarding the soil profile studied by [14], a layer of dark brown sandy and silty clay extends from the land surface to a depth of 7.5-8.5 m, then a Kurkar layer extends down under the first layer until the end of the testing borehole depth of 20 m. For the design of the infiltration technique, a layer of clean sand (sand layer) 1.0 m thick was applied and spread over the surface of the basin, the layer acts as a filter for any suspended solids that may be existing in the collected rainwater. A layer of non-woven geotextile was then laid directly under the sand layer, to allow stormwater to seep into the bottom soil preventing the sand grains from passage. Then two layers of gravel were spread under the upper layer of sand, the first with a depth of 20 cm and 5-10 mm size was spread under the non-woven geotextile layer at top of the second layer with a depth of 40 cm and 10-20 mm. The purpose of the gravel layer was to allow stormwater to seep down through the aggregate pores and imbibe through the boreholes that accelerate the infiltration rate bypassing the poorly permeable layers.

3. Waqf Basin

Waqf infiltration basin is located in Azaytoon area south of Gaza city (latitude 31°30'2.78"N and Longitude 34°27'31.62"E). First, the basin was designed and constructed using the natural surface spreading. Then, sequential development and upgrading steps occurred throughout different time phases. The catchment area is 6.0 km^2, where the basin is located in the lowest area to support collecting the incoming flow of stormwater by gravity [15], see Figure 3.

Figure 3: Waqf infiltration basin (Google map, 2022)

A. First Stage

Previously, Waqf basin used surface spreading of collected stormwater for infiltration. However, the low permeability of the soil layers underneath basin floor reduced the infiltration rate to unrecoverable levels. This raised the necessity of replacing the top soil layer of 6 m thick, with a new soil layer of higher permeability. The new upgraded system worked and has been in operation for the last 4 years with a design infiltration capacity of 49,826 m^3/day [15]. Meanwhile, the basin performance declined back to a low infiltration rate, owing to the existence of silt and clay (suspended solids) in the stormwater entering the basin. Thereby, the suspended solids settled to the bottom of the basin floor forming a thick and dense clogging layer that blocked the pores and significantly reduced the infiltration rate. Thus, another stage of system development and upgrade became necessary.

B. Second Stage

Waqf basin was recently upgraded in 2021 through the second stage of development by constructing 18 boreholes (drywells) at the end of the basin towards the west side. The distance between any two boreholes was around 12.0 m in two directions, each borehole of 355 mm diameter was cased with UPVC pipe [16]. The borehole pipes extended 16 m deep into the ground with a slotted depth of 10 m (20% open area), the pipes were fixed after digging the boreholes with a mechanical auger bucket, and then UPVC pipes were inserted into empty boreholes without filling by any media, see Figure 4. A gravel gabion (5-7 cm) was constructed over each borehole's upper tip, the gabion is a cubic shape of gravel with a side length of 1.5 m.

Figure 4: Borehole drilling and UPVC pipes installation at Waqf basin

The UPVC pipe extended through the gabion with a slotted area (20-25%) covered with plastic mesh as shown in Figure 5. HYDRUS (2D/3D) software was used for modeling and simulation of the infiltration system using the Richards equation. It was obtained that each borehole can infiltrate 232 m^3/day of stormwater. Thus, the design infiltration capacity of the basin was 3,480 m^3/day, obtained by multiplying the number of boreholes (18 boreholes) by the design infiltration capacity of each borehole (232 m^3/day/borehole)) as indicated in [16]. After the second stage of development, the soil profile underneath Waqf basin was classified by [16] as follows: the first layer (soil-sludge mixture) of 0.25 m, extending from the ground surface to a depth of 0.25 m, the second layer (yellowish imported fine sand) extended from the bottom of the first layer to a depth of 3.0 m. Then a third layer (yellowish imported coarse sand) extended from 3.0 m to 6.0 m depth, followed by layers of Kurkar, gravelly sand, and sandy gravel to a depth of 23.5 m where the water table was encountered.

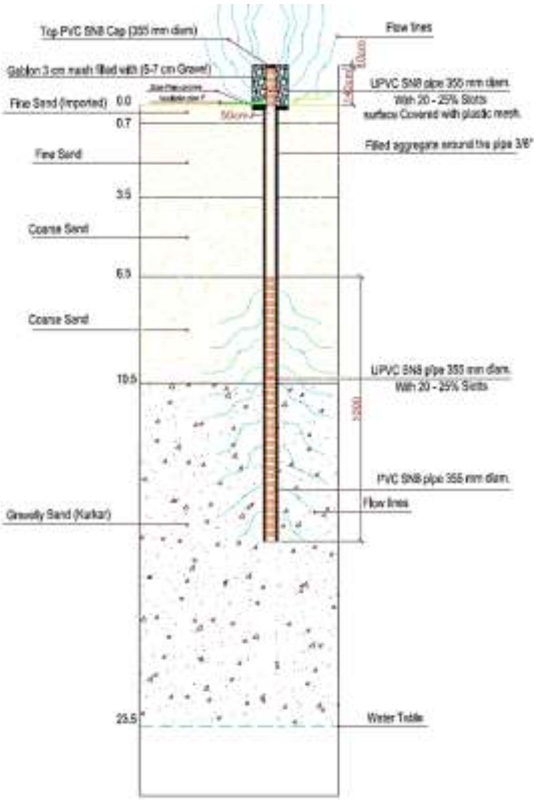

Figure 5: Borehole (drywell) profile at Waqf basin [16]

III. METHODOLOGY

Field measurement data driven approach was used in this study to estimate infiltration rate and capacity of each basin, where readings of water surface were recorded and compared during two wet seasons. The measuring unit of infiltration rate is (m/day) represented by the vertical net drop of ponded water level over 24 hours at each basin, (excluding inflow/outflow to the basin). In addition, the effect of water evaporation was also considered in this study, by deducting 2.39 mm/day (average evaporation rate during winter season in Gaza city) [17]. Equation 5 was used to calculate the net infiltration rate.

$$\text{Infiltration rate (m/day)} = \frac{\text{Net drop in water level (m)}}{\text{Elapsed time (day)}} \tag{5}$$

Thus, the actual infiltration capacity of a basin (volume of infiltrated stormwater) was obtained by multiplying net actual infiltration rate by basin floor area as expressed in Equation 6.

$$\text{Actual infiltration capacity } (m^3) = \text{Infiltration rate (m/day)} \times \text{Basin floor area } (m^2) \tag{6}$$

Then, infiltration efficiency was calculated by dividing the measured actual infiltration capacity of each basin (in the 2021-2022 wet season) by the design infiltration capacity of that basin, as expressed in Equation 7.

$$\text{Infiltration Efficiency (\%)} = \frac{\text{Actual infiltration capacity } (m^3/day)}{\text{Design infiltration capacity } (m^3/day)} \times 100 \tag{7}$$

1. Storm Events Under the Study

Five storm events with corresponding daily rainfall depths in mm were selected out of 37 rainy days occurred in the 2021-2022 wet season. Rainfall depths were recorded by the Ministry of Agriculture at each rainfall gauge station (17 manual gauge stations are available in the Gaza strip), and the rainy day number was also added to identify the temporal location of the 5 selected rainy days. The rainfall depths of both Waqf and Asadaqa basins were recorded through Atuffah gauge station. However, Alamal basin rainfall depth was recorded by west of Khanyounes gauge station, as shown in Table 1.

Table 1: The Five Strom Events Selected during the 2021-2022 Wet Season

Gauge Station	Governorate	Infiltration Basin	Storm Date				
			2021/12/17	15/01/2022	24/01/2022	5/2/2022	11/2/2022
			Rainy Day Number				
			7	17	21	27	29
			Storm Number				
			Storm 1	Storm 2	Storm 3	Storm 4	Storm 5
			Daily Rainfall Depth, mm				
Tuffah	Gaza	Waqf, Asadaqa	14.5	27.3	5.0	19.5	8.0
West Khanyounes	Khanyounes	Alamal	12.5	12.5	3.0	25.0	9.8

2. Methods of Measuring Water Level

The water level of ponded stormwater in the three infiltration basins (Waqf, Asadaqa, and Alamal) were measured after the 5 selected storm events in the 2021-2022 wet season, and compared to water level recorded in the 2017-2018 wet season through a previous study [18]. At Waqf basin, two methods were available to measure the water surface drop (equals indirectly the actual infiltration rate), first method was a measuring staff gauge placed at the middle of the basin near the southern side at (31°30'1.65"N, 34°27'32.36"E) while the second method was an electrical sonic ranger attached to a steel stand fixed above water surface to the basin southern side at (31°30'1.46"N, 34°27'32.37"E). The sonic ranger was proposed to send hourly data-log readings to a control panel located at the control room. However, it was not functioning properly at the time of this study, and re-calibration was required for accurate readings, see Figure 6.

Figure 6: Staff gauge and a sonic ranger panel at Waqf basin

At Asadaqa basin, water level was measured using staff gauges placed in the northern sub basin at (31°30'47.51"N, 34°28'33.50"E) and the southern sub basin at (31°30'40.47"N, 34°28'30.15"E). However, at Alamal basin the staff gauge was a marked ruler (marking lines) drawn on the concrete embankment of the basin.

3. Water Level Readings of Past Season

Old readings of water level during the past 2017-2018 wet season were recorded through a previous study [18], adding to a historical data set obtained from the Municipality of Gaza for Waqf and Asadaqa basins and Municipality of Khanyounes for Alamal basin. The readings of stormwater level at each basin were given in Tables 2 to 5.

Table 2: Waqf Basin old Records [18]

Storm No.	Date of Reading	Ponded Water Depth, m	Infiltration Rate, m/day
1	7/12/2017	1.05	-
	8/12/2017	1.00	0.05
	9/12/2017	0.95	0.05
2	27/12/2018	2.00	-
	28/12/2018	1.90	0.10
	29/12/2018	1.80	0.10
	30/12/2018	1.70	0.10
3	7/1/2018	3.80	-
	8/1/2018	3.50	0.30
	9/1/2018	3.20	0.30
	10/1/2018	2.90	0.30
	11/1/2018	2.70	0.20
4	1/3/2018	2.80	0.15
	2/3/2018	2.70	0.10
	3/3/2018	2.65	0.05
5	1/4/2018	1.43	-
	2/4/2018	1.42	0.01
	3/4/2018	1.41	0.01
	4/4/2018	1.40	0.01

Table 3: Asadaqa Basin old Records, South Basin [18]

Storm No.	Date of Reading	Ponded Water Depth, m	Infiltration Rate, m/day
1	6/12/2017	1.35	0.15
	9/12/2017	1.00	0.10
	16/12/2017	0.65	0.05
	23/12/2017	0.44	0.04
2	7/1/2018	1.70	0.28
	8/1/2018	1.42	0.22
	9/1/2018	1.20	0.10
	10/1/2018	1.10	0.07
3	30/1/2018	1.57	0.17
	31/1/2018	1.40	0.15
	1/2/2018	1.25	0.14
4	5/3/2018	0.80	0.04
	6/3/2018	0.76	0.02
	7/3/2018	0.74	0.01
	8/3/2018	0.73	0.01

Table 4: Asadaqa Basin old Records, North Basin [18]

Storm No.	Date of Reading	Ponded Water Depth, m	Infiltration Rate, m/day
1	25/12/2017	0.95	0.95
2	1/1/2018	0.80	0.90
3	7/1/2018	0.95	0.80
4	28/1/2018	1.35	0.35
	29/1/2018	1.00	0.20
	30/1/2018	0.80	0.20
	31/1/2018	0.60	0.15
	1/2/2018	0.45	0.14
	2/2/2018	0.31	0.11

Table 5: Alamal Basin old Records [18]

Storm No.	Date of Reading	Ponded Water Depth, m	Infiltration Rate, m/day
1	12/1/2018	3.45	0.20
	13/1/2018	3.25	0.15
	14/1/2018	3.10	0.15
	15/1/2018	2.95	0.14
2	2/2/2018	3.95	0.22
	3/2/2018	3.73	0.20
	4/2/2018	3.53	0.18
3	19/2/2018	3.85	0.05
	20/2/2018	3.80	0.05
	21/2/2018	3.75	0.05
4	12/3/2018	2.68	0.02
	13/3/2018	2.66	0.02
	14/3/2018	2.64	0.01
	15/3/2018	2.63	0.01

4. Water Level Readings of Present Season

During the 2021-2022 rainy season, current readings of the stormwater level in the three infiltration basins were measured on daily basis and collected at a specific time to ensure 24-hour period between every two consecutive readings.

The readings were taken after the end of each storm event and during a dormant period (rain free period) in order to measure the net drop in water level only due to the infiltration phenomena excluding any unrequired effects. The staff gauge readings (representing infiltration rates) were presented in Tables 6 to 9.

Table 6: Waqf Basin Recent Records

Storm No.	Time of Reading	Date of Reading	Ponded Water Depth, m	Infiltration Rate, m/day
1	11:00 am	12/17/2021	1.08	-
		12/18/2021	0.72	0.36
		12/19/2021	0.42	0.30
		12/20/2021	0.25	0.17
		12/21/2021	0.15	0.10
		12/22/2021	0.08	0.07
2	10:35 am	1/17/2022	4.95	-
		1/18/2022	4.37	0.55
		1/19/2022	3.85	0.52
		1/20/2022	3.40	0.45
		1/21/2022	3.00	0.40
		1/22/2022	2.70	0.30

3	12:15 pm	1/30/2022	4.77	-
		1/31/2022	4.30	0.47
		2/1/2022	3.85	0.45
		2/2/2022	3.50	0.35
		2/3/2022	3.20	0.30
		2/4/2022	2.97	0.23
4	8:00 am	2/6/2022	5.10	-
		2/7/2022	4.75	0.35
		2/8/2022	4.40	0.35
		2/9/2022	4.10	0.30
		2/10/2022	3.85	0.25
		2/11/2022	3.65	0.20
5	8:00 am	2/13/2022	4.38	-
		2/14/2022	4.20	0.18
		2/15/2022	4.04	0.16
		2/16/2022	3.90	0.14
		2/17/2022	3.77	0.13
		2/18/2022	3.67	0.10

Table 7: Asadaqa Basin Recent Records, South Basin

Storm No.	Time of Reading	Date of Reading	Ponded Water Depth, m	Infiltration Rate, m/day
1	11:00 am	1/17/2022	0.86	-
		1/18/2022	0.75	0.11
		1/19/2022	0.66	0.09
		1/20/2022	0.60	0.06
		1/21/2022	0.56	0.04
		1/22/2022	0.53	0.03
2	12:15 pm	1/30/2022	0.80	-
		1/31/2022	0.70	0.10
		2/1/2022	0.61	0.09
		2/2/2022	0.53	0.08
		2/3/2022	0.46	0.07
		2/4/2022	0.42	0.04
3	8:15 am	2/6/2022	0.80	-
		2/7/2022	0.73	0.07
		2/8/2022	0.66	0.07
		2/9/2022	0.60	0.06
		2/10/2022	0.55	0.05
		2/11/2022	0.51	0.04
4	8:15 am	2/13/2022	0.71	-
		2/14/2022	0.65	0.06
		2/15/2022	0.60	0.05
		2/16/2022	0.56	0.04
		2/17/2022	0.53	0.03
		2/18/2022	0.51	0.02

Table 8: Asadaqa Basin Recent Records, North Basin

Storm No.	Time of Reading	Date of Reading	Ponded Water Depth, m	Infiltration Rate, m/day
1	11:10 am	1/17/2022	0.42	-
		1/18/2022	0.25	0.17
		1/19/2022	0.14	0.11
		1/20/2022	0.07	0.07
		1/21/2022	0.04	0.03
		1/22/2022	0.02	0.02
2	12:20 pm	1/30/2022	No Readings	
		1/31/2022		
		2/1/2022		
		2/2/2022		
		2/3/2022		
		2/4/2022		
3	8:20 am	2/6/2022	0.67	-
		2/7/2022	0.47	0.20
		2/8/2022	0.30	0.17
		2/9/2022	0.14	0.16
		2/10/2022	0.04	0.10
		2/11/2022	0.01	0.03
4	8:20 am	2/13/2022	No Readings	
		2/14/2022		
		2/15/2022		
		2/16/2022		
		2/17/2022		
		2/18/2022		

Table 9: Alamal Basin Recent Records

Storm No.	Time of Reading	Date of Reading	Ponded Water Depth, m	Infiltration Rate, m/day
1	13:35 pm	1/17/2022	6.80	-
		1/18/2022	6.30	0.50
		1/19/2022	5.85	0.45
		1/20/2022	5.48	0.37
		1/21/2022	5.18	0.30
		1/22/2022	4.90	0.28
2	12:15 pm	1/30/2022	6.47	-
		1/31/2022	6.00	0.47
		2/1/2022	5.67	0.33
		2/2/2022	5.40	0.27
		2/3/2022	5.20	0.20
		2/4/2022	5.00	0.20
3	13:30 pm	2/6/2022	8.05	-
		2/7/2022	7.50	0.55
		2/8/2022	7.00	0.50
		2/9/2022	6.55	0.45
		2/10/2022	6.15	0.40
		2/11/2022	5.80	0.35
4	13:30 pm	2/13/2022	7.48	-
		2/14/2022	7.00	0.48
		2/15/2022	6.60	0.40
		2/16/2022	6.25	0.35
		2/17/2022	6.00	0.25
		2/18/2022	5.80	0.20

IV. Results and Discussion

1. Evaluation of Basins

In order to examine the difference between the three basins, several aspects should be considered starting with the comparison between the old readings (2017-2018 wet season) and the current readings (2021-2022 wet season) of infiltration rates. We can identify the changes in the basin efficiency in recent years and then compare the actual infiltrated volume of stormwater (from different seasons) to the design volume for the three basins. As is known, multiple parameters affecting the infiltration capacity of the artificial basins were not discussed in this study and should be considered in the author's future studies. The fully comparison of infiltration basins was elaborated in order to finally identify the best technique and most efficient infiltration technology that can be applied in the Gaza strip.

A. Waqf Basin

First, the old readings of Waqf basin during the 2017-2018 wet season showed that the infiltration rate (represented by the water level drop) did not exceed 30 cm/day at a water depth of 3.8 m, as shown in Table 2. At a water depth of 1.70 m, the infiltration rate was measured as 0.10 m, substituting into Equation 6 to get the following

Actual infiltration capacity = 0.10 (m/day) x 10,000 (m^2) = 1,000 m^3/day at a water depth of 1.70 m.

The design infiltration capacity of Waqf basin was estimated as 50,000 m^3 through a design report by [15]. Obviously, there was a big difference between the actual infiltration capacity (at old season) and the design infiltration capacity. The design report of [15] assumed that the entire basin floor area acts as an infiltration surface allowing stormwater to flow into the ground, as the bottom of the basin was replaced by more permeable layers (yellowish sand layers) than before, potentially promoting the infiltration rate for a while, however, the system malfunctioned again due to the accumulation of sediments at the basin floor which led to clogging and blocking of the soil pores with a significant decrease in the infiltration rate. The system failure was attributed to numerous factors such as; the low permeability of the underlying soil layers, the untreated stormwater incoming to the basin full of suspended substances, and lack of maintenance and repair of the basin (repair and cleaning after end of wet season); this may include replacing topsoil, which acts as a "bottleneck layer" preventing stormwater passage into the underlying soil layers. Other measures could be considered, for example, plowing, disking, and scrapping of the basin floor before every wet season, depending on field reconnaissance visits to determine the appropriate intervention.

Nonetheless, the Municipality of Gaza commenced the second stage of development for Waqf basin, which was completed in 2021. This time the upgrading of the basin involved the construction and drilling of 18 boreholes (drywells) as previously discussed. These boreholes greatly increased the infiltration rate, which was apparently ensured during the 2021-2022 rainy season when the infiltration rate reached 55 cm/day at a water depth of 4.95 m.

Figure 7: Graveled borehole gabion at Waqf basin: (a), (b)

The boreholes shown in Figure 7 have dramatically influenced the infiltration rate as they bypassed the relatively impermeable layers underneath the basin floor. however, this technique is still novel using empty UPVC pipes to keep the boreholes hollow, only for dribbling stormwater that pass through the on-basin floor graveled gabions. According to study [16], Richard's equation was used with HYDRUS (2D/3D) software (3D numerical modeling tool), each borehole infiltration capacity was 232 m^3/day, considering clogging and groundwater mounding effects that can reduce infiltration rate of the boreholes. Thus, the design infiltration capacity of 18 boreholes was estimated as 3480 m^3/day. However, the drop in the water level during (2021-2022 wet season) in Waqf basin was measured as 55 cm/day at a water depth of 4.95 m, as in Table 6. While, at a water depth of 1.70 m the infiltration rate was determined by the best fit regression model (power function relation) and estimated as 0.20 m/day, then we substitute into Equation 6, we get

Actual infiltration capacity as 0.20 x 10,000 = 2,000 m^3/day.

The previous result has shown the improvement in the infiltration rate of Waqf basin, which was very close to the design infiltration capacity obtained through the study [16], the boreholes were working properly according to the expected pre-planned capacity. Thus, the obtained infiltration efficiency of the system was estimated by substituting in Equation 7.

Infiltration efficiency (%) = 2,000 (m^3/day) /3,480 (m^3/day) = 57.47 %, at a water depth of 1.70 m in the 2021-2022 wet season.

The efficiency achieved demonstrated that Waqf basin has a highly efficient infiltration technique, which was obtained after the second stage of development and upgrade works. However, in Table 6, a decrease in the infiltration rate from storm 1 to storm 5 was observed due to the continuous accumulation of silt and clay during the same season. Therefore, an end of season maintenance program should be activated which may include backwashing of the boreholes gabions to clean and flush the plastic geotextile mesh covering the slotted areas around the UPVC pipes. See Figure 8 for the location of the 18 boreholes at Waqf basin.

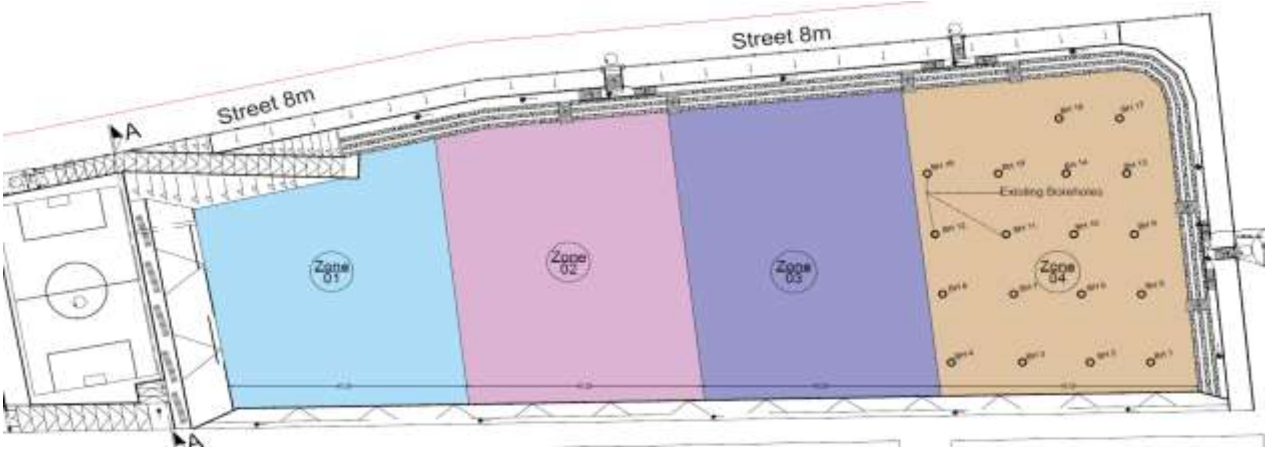

Figure 8: Location of 18 boreholes at Waqf basin

B. Asadaqa Basin

In Asadaqa Basin, the system was designed using a combination of drywells (vadose zone wells) and surface spreading, as in [14], with a total of 293 boreholes filled with gravel as previously mentioned. The design infiltration capacity of each borehole was estimated as 246 m^3/day, multiplying by the total number of boreholes, we get the design infiltration capacity as 72,078 m^3/day. Results showed that the system was working properly as tested and verified in 2016-2017 wet season [14]. However, the infiltration rate decreased over time, which was noticeable through water level readings in 2017-2018 and 2021-2022 rainy seasons, respectively. The average infiltration rate (south and north basins) at a water depth of 1.70 m in the 2017-2018 wet season was estimated as 0.34 m/day, as seen in Tables 3 and 4, respectively. Applying Equation 6 at both the southern and northern basins for the two rainy seasons, we get the following

Actual Infiltration capacity = 8,000 (m^2) x 0.34 (average infiltration rate of the two basins at a water depth of 1.7 m) = 2,743 m^3/day, in the 2017-2018 wet season.

However, the infiltration rate obtained from readings of southern and northern basins in the 2021-2022 wet season (Tables 7 and 8) was estimated as 0.11 and 0.2 m/day at water depths of 0.86 and 0.67 m, respectively. We used the best fit regression model (power function relation) as shown in Tables 7 and 8 to obtain the infiltration rate of 0.35 m/day at a water depth of 1.70 m, in the 2021-2022 wet season.

Actual infiltration capacity = 8,000 (m^2) x 0.35 = 2,800 m^3/day, thus, the infiltration efficiency was calculated by applying Equation 7.

Infiltration efficiency (%) = 2,800 (m^3/day) /72,078 (m^3/day) = 3.90 %, at a water depth of 1.70m in the 2021-2022 wet season.

The obtained actual infiltration capacity was very close to that obtained in the 2017-2018 rainy season, this demonstrated that the system was operating properly and no significant reduction in infiltration capacity was observed between the two seasons. However, the actual infiltration capacity of the two seasons was far from the design infiltration capacity, where the obtained infiltration efficiency did not exceed only 3.9 %, which highlighted the importance of repair and maintenance of the system. Considering that the graveled boreholes are difficult to clean by backwashing as they are drywells that only receive stormwater for recharge not reversely pumped in opposite direction. This may require replacing the clogged surface layer of yellowish fine sand that acted as a filter for stormwater before passing into groundwater.

C. Alamal Basin

Alamal basin is applying only surface spreading technique with no infiltration wells or drywells. In the 2017-2018 and 2021-2022 rainy seasons, the readings of water levels were recorded in a similar way. The actual infiltration capacity in the 2017-2018 wet season was expressed as

Infiltration capacity = 17,000 (m^2) x 0.0062 = 105.4 m^3/day, at a water depth of 1.7 m.

Using the best fit regression model (power function relation) of the recorded readings in Table 9, the infiltration rate was estimated as 0.037 m/day at a water depth of 1.70 m in the 2021-2022 rainy season, and the actual infiltration capacity was estimated as 629 m^3/day. Hence, the infiltration efficiency was calculated by applying Equation 7 as follows

Infiltration efficiency (%) = 629 (m^3/day) /13,670 (m^3/day) = 4.60 %, at a water depth of 1.70m in the 2021-2022 wet season.

We found a very low infiltration efficiency due to the large difference between the design infiltration capacity and the actual infiltration capacity in the 2021-2022 wet season. The accumulation of sediments (suspended solids) that form a thick and dense layer of silt and clay was the reason for the significant reduction in the actual infiltration capacity, which worsened over time, especially when there was no regular repair and maintenance program for Alamal basin.

2. Comparison of Three Basins

Previous sections showed the water level readings recorded at the basins during two wet seasons, we noticed the difference in the efficiency, which depends on several factors, one of the main factors was the geological characteristics of the soil underneath basin floor, this factor can identify the applicable infiltration technique prior to design phase. When soil layers with accepted permeability and saturated hydraulic conductivity with no clay lenses or confined aquifers, the surface spreading technique is applicable and efficient such as in Alamal basin that used the same technique.

More importantly, this technique should be used when mixing of sewage with stormwater is likely. Therefore, the SAT system (Soil Aquifer Treatment) takes the role of filtering contaminated stormwater before infiltrated into the aquifer. However, water resources for surface recharge systems should be of adequate quality to prevent excessive clogging of infiltrating surface. The clogging of infiltrating surface and consequent reduction in infiltration rate is the bane of all artificial recharge systems. Minimizing the effects of clogging may require pretreatment of stormwater to reduce suspended solids, nutrients, organic carbon, and regular drying of the system to allow for peeling, cracking, and physical removal of clogging layer. This has reduced the infiltration efficiency of Alamal basin to 4.6% as in the 2021-2022 wet season due to the lack of any repair and maintenance program.

The technique used at Asadaqa basin is a combination of surface spreading and deep recharging using graveled drywells (vadose zone wells). The technique was used because the surface soil layer was of low permeability (dark brown sandy and silty clay) and its thickness was too large to be replaced or removed. The boreholes were drilled and distributed over the entire area of the basin surface in order to accelerate the imbibition of stormwater into the deep soil layers.

With this technique, collected stormwater should not mix with wastewater or even clean stormwater only could enter the basin. Asadaqa basin was functioning properly with a reducing infiltration rate over time as previously described by the water level readings obtained during the wet seasons studied. The infiltration efficiency was significantly reduced to about 3.90 % in the 2021-2022 wet season compared to the design infiltration rate.

The main advantage of recharging trenches or wells (drywells) in the vadose zone is that they are relatively inexpensive. However, the disadvantage (low infiltration efficiency of 3.90 %) is that they eventually clog up at their infiltrating surface due to the accumulation of suspended soils and/or biomass. Since they are in the vadose zone, boreholes cannot be redeveloped or backwashed to restore infiltration efficiency. In order to minimize clogging, water should be pretreated before infiltration or a sand filter should be placed with possibly a geotextile fabric on top of backfill as discussed earlier in this study.

At Waqf basin, a combination of surface spreading and drywells was applied, however, the drywells are not graveled and surface spreading was ignored and neglected. The technique was used since the underlying soil media was of low permeability, therefore the surface spreading did not function adequately as per the design infiltration capacity. The technique was novel and emerging technology since the drilled boreholes were empty and not filled with gravel, extending into vadose zone without reaching groundwater table, leaving only 6.0 m to clean the infiltrated stormwater with SAT system. This raised the necessity to discharge only high quality water into the basin (pretreated) to avoid clogging of the infiltrating shafts (drywells) and the closure of slotted area on pipes permitter that cannot be backwashed reversely for cleaning. The technique proved a good performance during the 2021-2022 wet season, with a high infiltration efficiency of 57.47 %.

Table 10: Comparison of Three Basins

Parameter	**Waqf Basin**	**Asadaqa Basin**	**Alamal Basin**
Catchment Area (km^2)	6.0	2.5	10.0
Basin Floor Area (m^2)	10,000	8,000	17,000
Infiltration Technique	Non graveled boreholes (drywells)	Graveled boreholes (drywells)	Surface spreading
No. of Boreholes	18	293	N/A
Capacity of Borehole (m^3/day)	232	246	N/A
Soil Type	Yellow fine sand, yellow coarse sand, Gravelly sand and sandy gravel	Dark brown sandy and silty clay, Kurkar	Highly heterogeneous with relatively impermeable clay layers
Design Infiltration Capacity (m^3/day)	3,480	72,078	13,670
2017-2018 Wet Season at a Water Depth of 1.70 m			
Infiltration Rate (m/day)	0.10	0.34	0.0062
Infiltration Capacity (m^3/day)	1,000	2,743	105.4
2021-2022 Wet Season at a Water Depth of 1.70 m			
Infiltration Rate (m/day)	0.20	0.35	0.037
Infiltration Capacity (m^3/day)	2,000	2,800	629.0
Infiltration Efficiency (%)	57.47	3.90	4.60

The regular maintenance and repair program that involves cleaning and backwashing of both gabions and the plastic geotextile mesh was important before every winter season.

Table 10 presents a comparison of three basins in terms of several themes, in which we found that the infiltration capacity of Waqf basin doubled from 1,000 m^3/day to 2,000 m^3/day from the 2017-2018 wet season to the 2021-2022 wet season, respectively, due to the development and upgrade works that were recently carried out by constructing the 18 boreholes with an infiltration efficiency of 57.47 % as previously discussed. The technique was accepted and proved to be a highly efficient infiltration system and a novel solution to the long drainage time at Waqf basin. The full modeling and simulation of the basin using a total of 18 boreholes needs to be performed to realistically verify the design infiltration capacity of the basin at various stormwater levels.

Whereas at Asadaqa the actual infiltration capacity between the two wet seasons was almost the same at around 2,800 m^3/day, but with a very low infiltration efficiency of 3.90 %. Any upgrade of the system will be very expensive, which may require removing the entire clogged layers and cleaning the geotextile layers, then fixing them back and backfilling with clean layers of fine sand as before.

At Alamal basin, the actual infiltration capacity was also increased to 629 m^3/day in the 2021-2022 wet season compared to the 2017-2018 wet season of only 105.4 m^3/day, and this was attributed to the repair and maintenance that was performed for the basin surface layers such as disking and scrapping of clogging sediments layers before the start of the 2021-2022 wet season. Despite this, the infiltration efficiency of 4.60 % was still very low, which may be due to the inaccurate design infiltration capacity of [13], where the hydraulic conductivity and hydraulic gradient changed significantly over time, resulting in a changed infiltration rate.

It was also evident that Asadaqa basin has the highest infiltration rate compared to other basins but not the highest infiltration efficiency, that was noticed through some field visits during specific rainy days where no stormwater was retained in the basin, Figure 9.

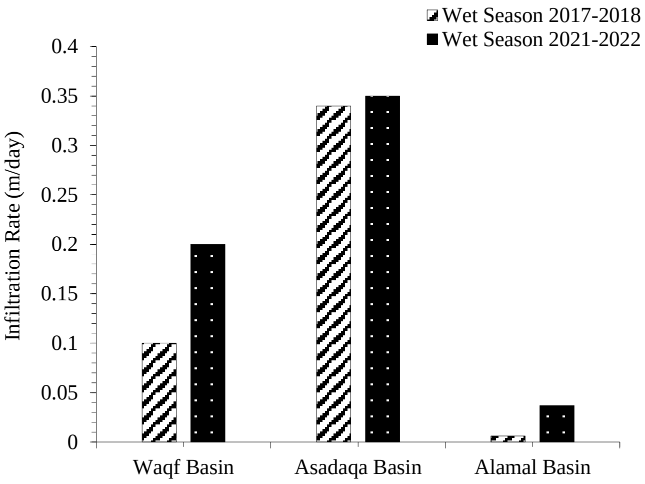

Figure 9: Infiltration rate of three basins at two wet seasons

It is worth noting that the water depth of 1.70 m was selected to compare and study the differences between the basins in different wet seasons since the variation in water depth affects the infiltration rate, and infiltration rates at a water depth of 1.7 m in the 2017-2018 wet season were already recorded in the study [18] and then compared to the results of the 2021-2022 wet season.

Figure 10 shows the change in the infiltration rate over time for the three infiltration basins during specific storm events superimposed in one graph. The first storm event was selected for each wet season because the infiltration rate at the basins varies over time and thus the infiltration rate also changes during the same wet season from storm 1 to storm 5 owing to the continuous biofouling and siltation of basin floor.

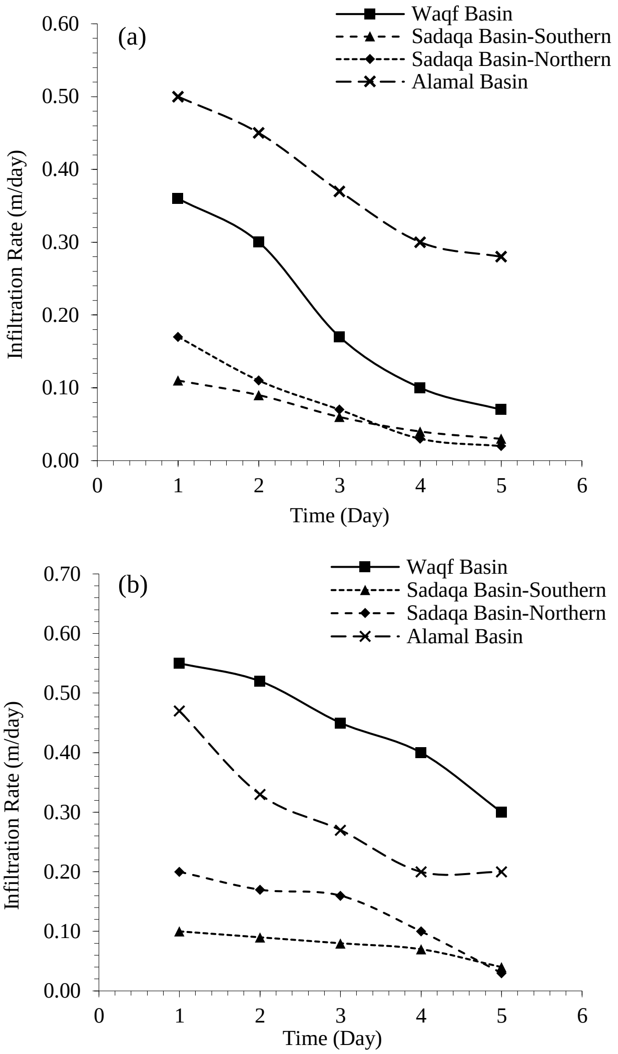

Figure 10: Infiltration rate of three basins over time: storm1 (a), storm2 (b)

V. CONCLUSION AND RECOMMENDATION

Stormwater infiltration is important and indispensable for groundwater recharge. In this study, three infiltration techniques were investigated in the Gaza strip involving, surface spreading, surface spreading combined with graveled boreholes, and surface spreading combined with non-graveled boreholes. The techniques were compared over two wet seasons and the actual infiltration capacity was compared with the design infiltration capacity at each basin. Infiltration efficiency (%) was also calculated for each basin, studied, discussed, and then compared to others. The infiltration technique used at Waqf basin has definitely shown a significant increase in the actual infiltration capacity of 2,000 m^3/day at a water depth of 1.70 m in the 2021-2022 wet season with the highest infiltration efficiency of 57.47%.

While the technique used at Asadaqa basin was still functioning properly without significant reduction in the actual infiltration capacity between the two wet seasons (2,743 m^3/day in the 2017-2018 wet season and 2,800 m^3/day in the 2021-2022 wet season). Despite this, Asadaqa basin was of the lowest infiltration efficiency of 3.90% compared to other basins since the soil pores were clogged, thereby preventing stormwater from passing through top soil layers to the graveled boreholes and then to groundwater. The low infiltration efficiency was attributed to the lack of repair and maintenance program that should be put in place by local municipalities.

The infiltration rate at Alamal basin needs further improvement as the infiltration efficiency was only 4.60%, and this can be performed by drilling drywells (boreholes) which can accelerate infiltration rate into the underlying soil layers provided that the collected stormwater is clean, safe, and not mixed with wastewater to protect groundwater from contamination. It is recommended that future studies focusing on the factors affecting infiltration rate should be conducted to furtherly evaluate the most efficient technique that can be applied in the Gaza strip, associated with an accurate quantification of surface runoff at winter season to precisely determine the volume of incoming stormwater in each basin. Nonetheless, in-depth studies and investigations should be conducted for Waqf basin to estimate the infiltration capacity using software modeling tool and the effectiveness of increasing the number of drilled boreholes with the same emerging technique.

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