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Factors Affecting the Infiltration Rate of Stormwater

(Case Study: Three Large Stormwater Infiltration Basins in the Gaza Strip)

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Abstract— Surface runoff from rainfall is an important source of fresh water and when properly utilized, is considered to be of major importance to the Gaza coastal aquifer. The artificial infiltration systems are the most important and renowned groundwater recharging and replenishing methods practiced in the Gaza Strip a few years ago. The main objective of this study is to investigate the critical factors affecting the infiltration rate in three large infiltration basins (Waqf, Asadaqa, and Alamal) existing in the Gaza Strip and apply different infiltration techniques. The study of the three basins was conducted in the two rainy seasons; 2017-2018 and 2021-2022, during which water depth readings were collected and compared.

The effect of both water depth and suspended particles on the infiltration rate was studied and compared between the two rainy seasons for the three infiltration basins. The results revealed that an increase in water depth of stormwater in the infiltration basin leads to an increase in infiltration rate in a power function relationship over time. This relation was linearly proportional at the earlier stages of infiltration, but after a while, the infiltration rate became less than linear or stopped increasing as water depth increased. The effect of clogging was also investigated as part of this study and the results showed that the progressive accumulation of sediment and suspended particles entering the basin with the inflowing stormwater significantly reduced the infiltration rate in the three basins over time. The sediment composition at Waqf basin was analyzed at the mid and end of the 2021-2022 rainy season, which resulted in the amount of silt and clay (dominant clogging material) increasing from zone 1 to zone 4. At zone 4, silt and clay accounted for 27%. and 22.5% (at mid-season), 30.8%, and 23.3% (at end-season) of the sediment, respectively.

The results also showed that the sediment thickness at Waqf Basin increased from zone 1 to zone 4 owing to that the 18 drill boreholes (drywells) functioned as water drainage points seeping the collected stormwater into the underlying soil layers.

As a recommendation for future developmental works at Waqf basin, a new series of drilled boreholes should be added in zone 3 in addition to installing a geotextile mesh membrane as a vertical separation filter wall between different zones to reduce turbidity and suspended solids and protect the infiltration basin from clogging tendency.

Index Terms—Infiltration, Water depth, Clogging, Suspended particles, Sediment layer.

I. INTRODUCTION

The Gaza Strip lacks a sufficient amount of fresh water to meet the increasing needs of the people over time. Groundwater is considered the most important continuous and inherent water source, which is suffering nowadays in terms of quantity and quality. However, rainfall could be seen as the only source capable of mitigating the rapid degradation of groundwater due to the huge abstraction of the Gaza Coast aquifer without a crucial offset during the rainy season.

Millions of cubic meters of surface runoff in the Gaza Strip are either discharged into seawater or accidentally mixed with sewage and then pumped into sewage treatment plants, putting additional pressure on the efficiency of treatment plants, not to mention the loss of freshwater as the main source of supply to the aquifer. The recharging industry emerged in the Gaza strip a few years ago, and several studies have been conducted to investigate the efficiency and the impact of stormwater recharging on the water resource management plan.

One of the world's most renowned recharge methods is the artificial infiltration basin (pond), which is actively used in arid and semi-arid regions, playing an essential role in preserving freshwater from wasting and preventing irremediable depletion of the groundwater table. Stormwater infiltration is the spreading of the surface runoff (rainfall excess) over the basin floor surface, allowing accumulated stormwater to seep gradually downwards into the soil. Thus, the stormwater is collected, retained, and ponded at the infiltration basin and then absorbed into soil deep layers under the force of gravity over time. Therefore, gravity is considered to be the driving force of stormwater drainage through soil pores, displacing the air trapped in the soil voids until percolating into the groundwater. The utilization of Gaza's artificial infiltration basins could be the future life jacket of Gaza's worsening water crisis. This has dedicated the importance of fully understanding the infiltration technology and techniques that can be applied locally in the Gaza strip. In this study, three large infiltration basins (Waqf, Asadaqa, and Alamal) with different infiltration techniques were selected to study the factors affecting the infiltration rate. The results obtained were then compared to investigate the effect of water depth, suspended solids, time, and stormwater quality on the infiltration rate in two rainy seasons. Then, the sediment layer at the bottom of Waqf basin was measured and analyzed to study the composition of the sediment and its thickness in the mid and end of the 2021-2022 rainy season. Finally, the obtained results were compared to the previous results in the literature to identify the most important factors that reduce the infiltration rate over time and accordingly help to identify the most appropriate infiltration technique in the Gaza strip.

II. SUMMARY OF THREE BASINS

The main objective of this study is to investigate the factors affecting the infiltration rate at three existing artificial infiltration basins in the Gaza strip. The three basins (Waqf, Asadaqa, and Alamal) used different infiltration techniques. Waqf basin is located in Gaza city near Azaytoon area, the basin applied the surface spreading technique combined with the un-graveled 18 drilled boreholes (drywells not backfilled with gravel) and cased with 355mm diameter UPVC pipes.

Each upper pipe head was surrounded by gravel gabions (1.2 x 1.2 x 1.2 m cube of coarse gravel) which act as an absorbing drainage point for the stormwater collected in the basin, further details are available in the research paper [1] which is under the process of publication.

Asadaqa basin is located also in Gaza city, near Atuffah area, where the used surface spreading method was augmented by adding graveled 293 boreholes (drywells backfilled with gravel), the boreholes were drilled with a mechanical bucket drill, and gravel was stacked in each borehole, and topsoil layers were spread on the top surface of the basin to improve the infiltration rate with a higher permeability soil matrix [1].

Alamal basin is located in Khanyounes Governorate in the southwestern Gaza strip, where the basin used the natural surface spreading with no recharging boreholes. Thus, the collected incoming stormwater was retained in the basin and gradually infiltrates into the soil formation under gravity force and then percolates to the groundwater table. Waqf and Asadaqa infiltration basins were both managed and monitored by the Municipality of Gaza while Alamal basin was managed and monitored by the Municipality of Khanyounes. For more information on the three basins, see the study [1]. Figure 1 shows the wide variety of artificial infiltration methods [2].

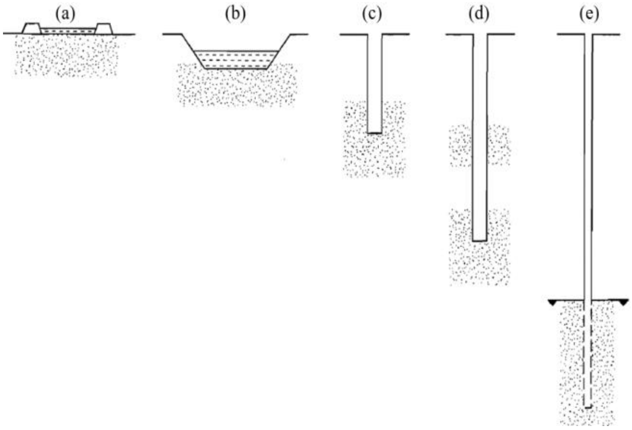


Figure 1: Several recharge techniques: surface spreading basin (a), excavated basin (b), trench (c), drywell /borehole or vadose zone well (d), recharge or aquifer well (e), after [2].

At the three basins, the decreasing water depth was measured with staff gauges installed at each basin to measure the varying ponded water depth during the rainy season.

III. FIELD OF STUDY

Daily field visits (every 24 hours) were performed during the 2021-2022 rainy season at the three basins to measure the stormwater depth in each basin. The decrease in water depth over time indirectly represents the stormwater infiltration rate with a measuring unit (m/day), as it is the amount of water absorbed by the soil media over time through a unit surface area of the basin floor. Other effects such as temperature and evaporation of the open water bodies were necessarily taken into account, with the evaporation depth in the Gaza strip being estimated at 2.39 mm/day. Thus, the actual infiltration depth on the selected rainy day was calculated by subtracting the evaporation depth from the total drop in water depth, then dividing the water depth obtained by the 24 hours (time lapse of readings) to give the net infiltration rate in (m/day) [1].

In addition, the water depth measurements were successively carried out at a time when there was no inflow or outflow from the basins to exclude the influence of unwanted factors on the basin's water depth. In the 2021-2022 rainy season, the water depth readings in each basin for 5 storm events were recorded and collected in tables as detailed in the study [1] and then compared to the readings from the past 2017-2018 rainy season. The results of the study [1] showed that the efficiency of the three basins differed and was estimated to be 57.47%, 3.90%, and 4.60% for Waqf, Asadaqa, and Alamal basins, respectively. The high infiltration efficiency of Waqf basin was attributed to the newly drilled 18 boreholes (drywells) which increased the basin's infiltration rate.

In this study, empirical expressions were created and analyzed to study the effect of multiple factors on the infiltration rate of the three basins. Then a study was conducted to analyze the sediment thickness and composition at Waqf basin in the middle and end of the 2021-2022 rainy season.

1. Selected Wet Season

The current 2021-2022 rainy season was selected for this study; according to the Ministry of Agriculture, the season comprised 37 rainy days and only 5 rainy days (storm events numbered from storm 1 to storm 5) distributed temporally over the time span of the wet season were selected to investigate the factors affecting the infiltration rate, provided that the five selected rainy days were followed by 5 dormant days (non-rainy days for collecting readings) to avoid the effect of the incoming flow and the rainfall itself on the height of ponded stormwater at the basin.

The rainfall depths of the five storm events were recorded by the manual rainfall gauge stations (17 rainfall gauge stations are available in the Gaza strip), where the rainfall depths at both Waqf and Asadaqa basins were recorded by Atuffah gauge station while the western Khanyounes gauge station was used to record the rainfall depths at Alamal basin.

With the help of the Ministry of Agriculture, the rainfall depths at the gauge stations were only recorded on daily basis not hourly. Another past 2017-2018 wet season was selected by [3], to study the three infiltration basins by recording the daily infiltration rates (drop in water depth), then comparing the in-situ infiltration capacity with the design infiltration capacity, as performed in the study [1].

Table 1 shows the rainfall information for the selected five rainy days.

Table 1: Rainfall Data of the 5 Storm Events at the 2021-2022 rainy season [1]

Gauge Station	**Governorate**	**Infiltration Basin**	**17/12/2021**	**15/01/2022**	**24/01/2022**	**5/02/2022**	**11/02/2022**
			Storm 1	Storm 2	Storm 3	Storm 4	Storm 5
			Daily Rainfall Depth, mm				
Atuffah	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. Factors Affecting Infiltration Rate

The infiltration process is a complex phenomenon involving a large number of macroscale processes that were influenced by the behavior of the micro-scale processes occurring during the infiltration process. In this regard, two approaches were studied a few years ago, the conceptual approach based on field measurements and observations, and the realistic phenomenal approach, which studied the physical and chemical processes occurring at the scale of soil pores.

Therefore, many empirical and experimental models were created to simulate the infiltration process and study the effect of many factors such as water depth, stormwater quality, suspended solids, soil characteristics, water table, vegetation cover, land slope, soil degree of saturation, rainfall intensity, evaporation and temperature, and human activities.

Kostiakov [4] and Horton [5,6] are considered to be the best known empirical equations used to represent the infiltration rate. The equations created have critical limitations that may hinder their application. Because they depend on complicated parameters that cannot be readily estimated from the available soil information. The other very important physical models of the infiltration process were expressed by Philip [7] and Green-Ampt [8], both of which used parameters and information that can be obtained from soil data, particularly that of Green- Ampt model. In addition, Fok [9] summarized in his study the development and limitations of using the various infiltration models. Many others have studied the infiltration process in depth such as Richards, Bouwer, Todd, Van Genechten-Mualem, Horton, and Massmann creating various models and empirical expressions to represent and express the water infiltration phenomena.

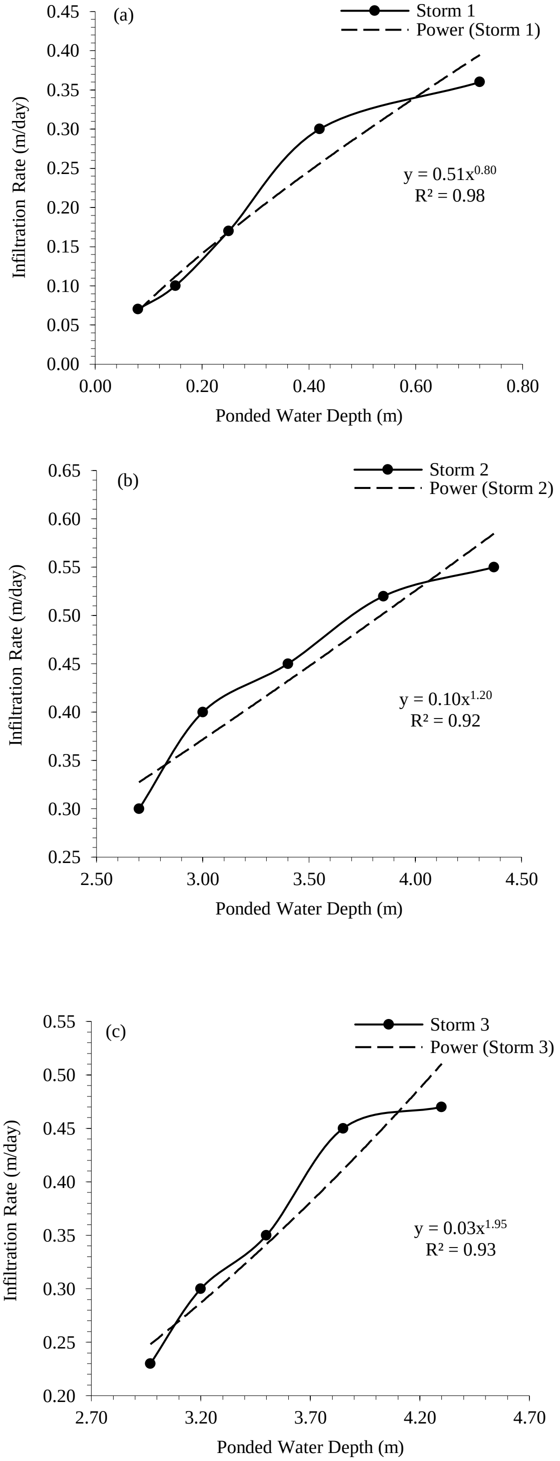
In this study, only three factors that can affect the design of the infiltration basin were investigated at the three infiltration basins; Water depth, suspended solids, and the composition of the sediment as a clogging factor.

IV. RESULTS AND DISCUSSION

1. Effect of Water Depth

Infiltration rate is directly affected by the height of stormwater retained in the infiltration basin, so increasing the depth of ponded water leads to an increase in the infiltration rate, and this was evidently found during the study of the three infiltration basins; (Waqf, Asadaqa, and Alamal) in the 2017-2018 wet season. The following figures show the adopted increase in the infiltration rate, as the water depth increased resulting in additional hydraulic pressure on the basin bottom surface leading to more stormwater seeping into the underlying soil layers thus accelerating the infiltration rate.

The influence of water depth on the infiltration rate was investigated for numerous storm events that occurred in the 2021-2022 rainy season (from storm 1 to storm 4). After each storm event, the water depth was measured on a daily basis to record the net drop in the water surface at every basin. Readings of ponded water depth were collected and plotted versus the infiltration rate (drop in water level) in m/day, see Figure 2 for Waqf basin.



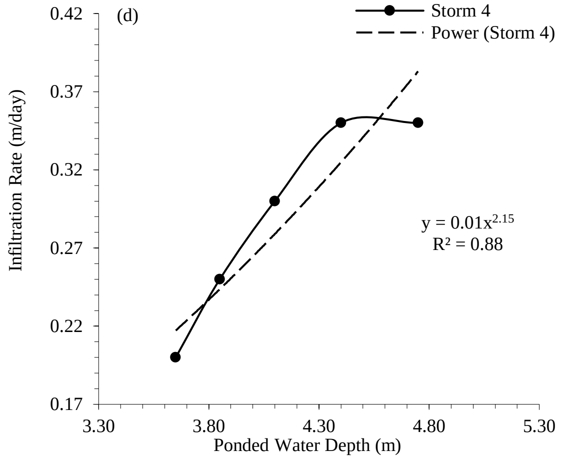
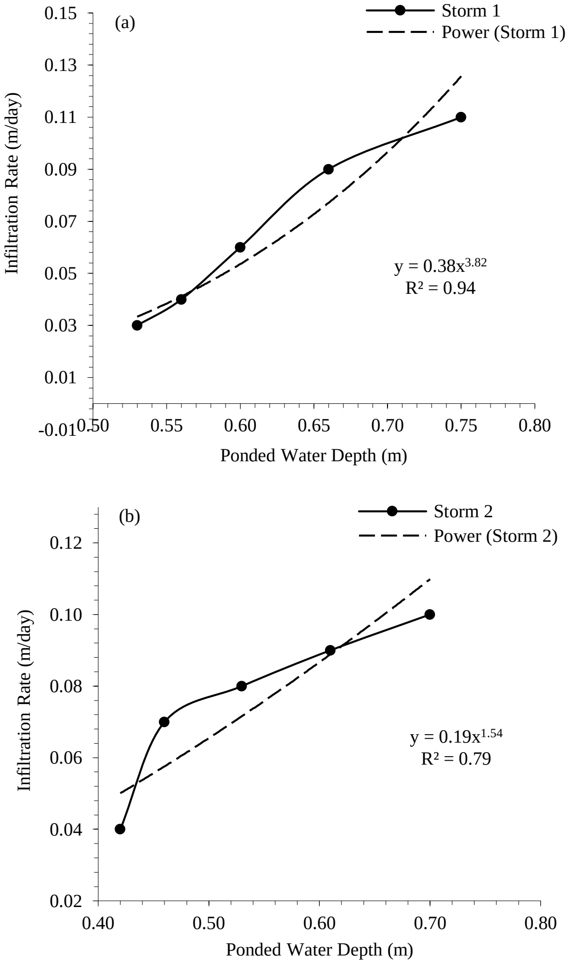


Figure 2: Effect of water depth on infiltration rate at Waqf basin: storm1 (a), strom2 (b), storm3 (c), strom4 (d)

The same is true for Asadaqa basin, water depth readings were collected at both the southern and northern basins (Asadaqa basin consists of two basins) as described in [1], and compared to the infiltration rate as in Figures 3 and 4, respectively. Knowing that the water depth readings were only recorded for storms 1 and 3 at the northern basin, as the other storms did not create stormwater ponding to be measured.



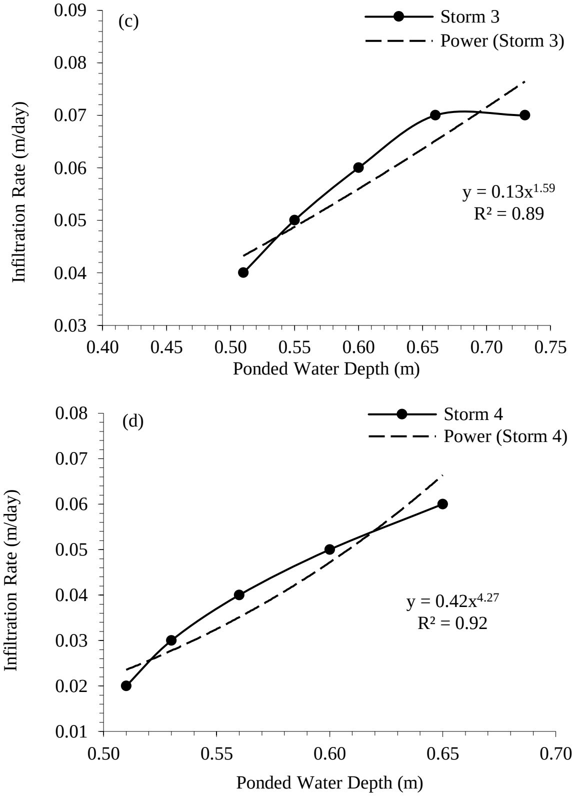


Figure 3: Effect of water depth on infiltration rate at Asadaqa south basin: storm1 (a), strom2 (b), storm3 (c), strom4 (d)

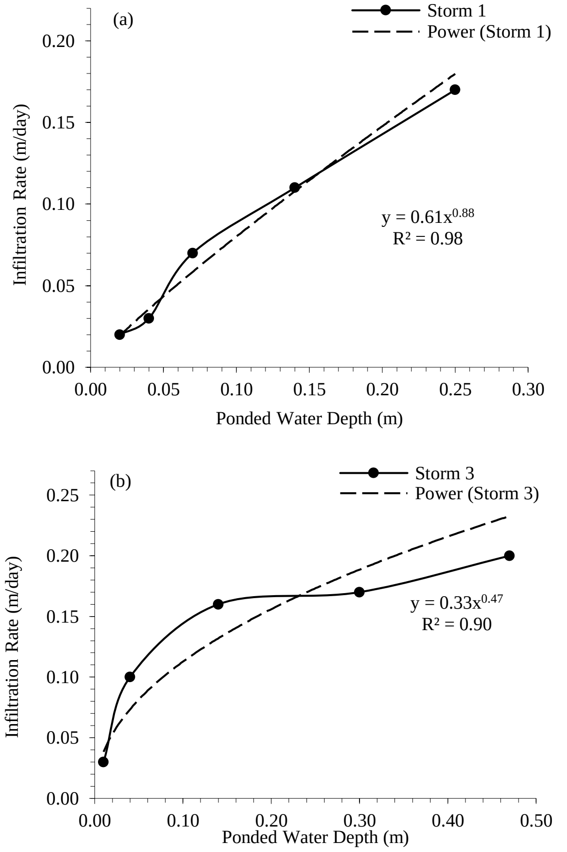


Figure 4: Effect of water depth on infiltration rate at Asadaqa north basin: storm1 (a), strom3 (b)

At Alamal infiltration basin, the water depth readings were obtained at the four storm events, and curves were drawn to show the relation with the infiltration rate, as seen in Figure 5.

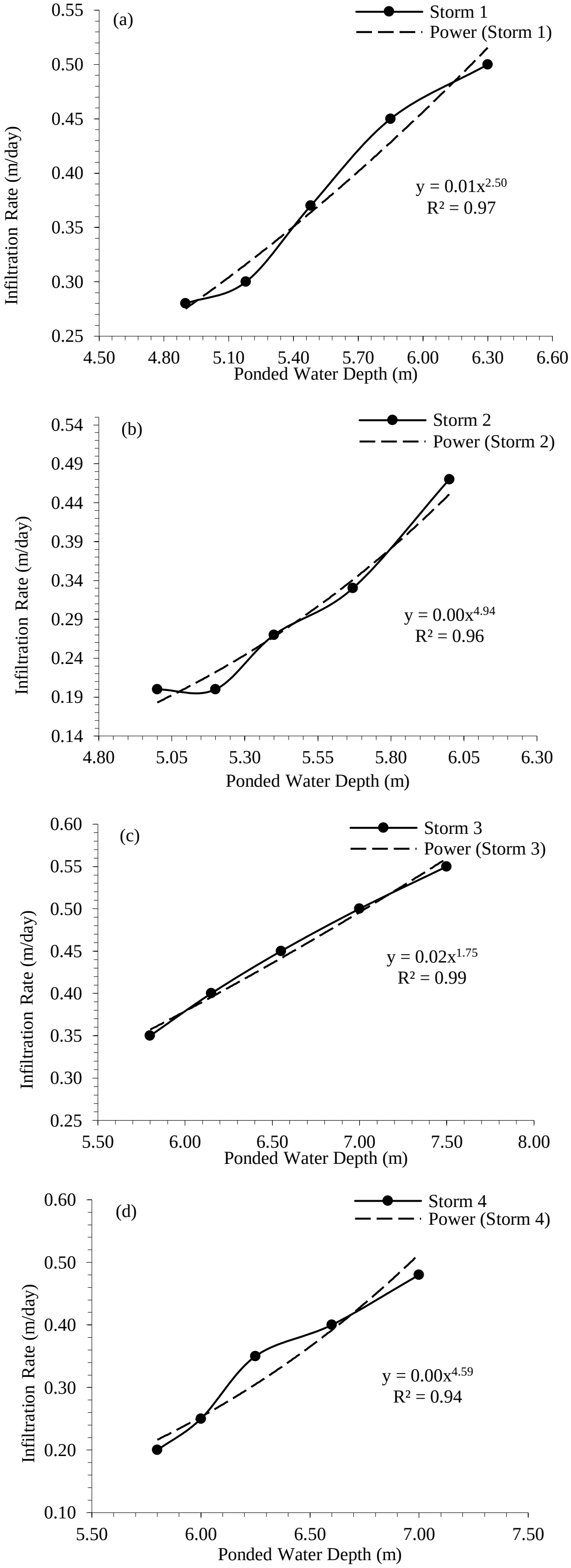


Figure 5: Effect of water depth on infiltration rate at Alamal basin: storm1 (a), strom2 (b), storm3 (c), strom4 (d)

Studying the previously obtained figures and the effect of water depth on the infiltration rate, one can see that the increase in water depth explicitly leads to an increase in the infiltration rate in the three infiltration basins, but at different rates. Furthermore, we found that the increasing infiltration rate was proportional to the increase in water depth, up to a certain limit, after which the infiltration rate stopped increasing due to the increase in water depth. The time elapsed during the rainy season showed that the infiltration rate varied during the rainy season as well as storm events in the three basins, meaning that the earlier storm events during the rainy season (e.g. storm 1) produced a higher infiltration rate than the last storm events (e.g. storm 3 or 4). Irrespective of the water depth, the infiltration rates of earlier storm events were higher than those of later storms, even with the same water depth of stormwater.

The decreasing infiltration rate from storm 1 to storm 4 was attributed to the suspended silt, clay, and other fine particles found in the stormwater entering the infiltration basin. The sediment layer of suspended material formed a dense and thick layer commonly known as a “cake barrier” or “filter cakes” as mentioned in [10]. This layer significantly lowered the infiltration rate due to its low permeability and low hydraulic conductivity, thus becoming the control layer that hardly allows stormwater to penetrate through the basin floor to the downward layers of soil.

From the previous figures, it was clear that the relation between the infiltration rate and the ponded water depth was a power function relation, which can be written as in Equation 1.

$$f(x) = a\,x^{b} \tag{1}$$

Where $f(x)$ is the infiltration rate (m/day); x is the ponded water depth (m); a and b are dimensionless curve-fitting parameters defined by model regression. For instance, the power function of storm 1 at Waqf basin was expressed in Equation 2 as shown in Figure 2

$$y = 0.51x^{0.80} \tag{2}$$

Equation 2 is an empirical expression in the form of a power function obtained from the experimental and field observation and used to describe the behavior of the infiltration rate with respect to water depth.

Therefore, the proposed power functions of the infiltration rates at the three infiltration basins within the different storm events all decreased monotonically with the decrease in water depth, the decrease was associated with the values of both the a and b coefficients. Considering that the coefficients a and b generally have no physical meaning in general and were only evaluated by the best fit regression curve for field obtained data.

Thus, each storm event has a specific power function and consists of varying coefficients a and b. Therefore, it was difficult to obtain a universal power function (empirical expression) that would apply to all cases as the in-situ conditions of the three basins varied over time (from storm1 to storm4). In addition, the thickness of the sediment layer at the bottom of the basin increases, as it continuously receives suspended solids, thereby degrading the infiltration efficiency regardless of the stormwater depth. The coefficients of Equation 2 were estimated as $a = 0.51$ and $b = 0.80$ for storm 1 at Waqf basin, which was evident in Figure 2-(a), however different values were obtained at storm 2 as $a = 0.10$ and $b = 1.20$ as in Figure 2-(b), etc. for the storms 3 and 4 as well as for the other infiltration basins we obtained different coefficients.

Studying the R^2 (r-squared or coefficient of determination) showed how well the field data fit the regression model and this illustrated the degree of fitting goodness with the regression model at each infiltration basin within each storm event. R-squared of the power function can take values ranging from 0 up to 1 based on the fit goodness of the field data. Hence, at Waqf basin with storm 1, $R^2 = 0.98$ as shown in Figure 2-(a), indicating high goodness of fit and that the power function obtained explained well the water depths recorded in the field. The other storm events yielded different regression models with different values of r-squared as shown in Figures 2-(b), (c), and (d).

The study [3] also investigated the effect of the water depth on the infiltration rate at the three basins; Waqf, Asadaqa, and Alamal basins during the 2017-2018 rainy season. The suggested regression models of the field obtained data were a proportional linear function as expressed in Equation 3

$$y = 9.0863x - 5.8579 \qquad (3)$$

Where y is the infiltration rate (cm/day), and x is the height of ponded water (m) and with the r-squared = 0.91 as shown in Figure 6. The linear function did not properly represent the effect of water depth on infiltration rate, because the effect of water depth decreased over time and cannot be represented by a first-order linear function.

In addition, the r-squared was less than 0.95 indicating the inaccurate fit of the field data using the linear function. The study also investigated the water depth readings obtained from only one storm event (storm 3) during the 2017-2018 rainy season and excluded the other storm events that can result in different infiltration rates.

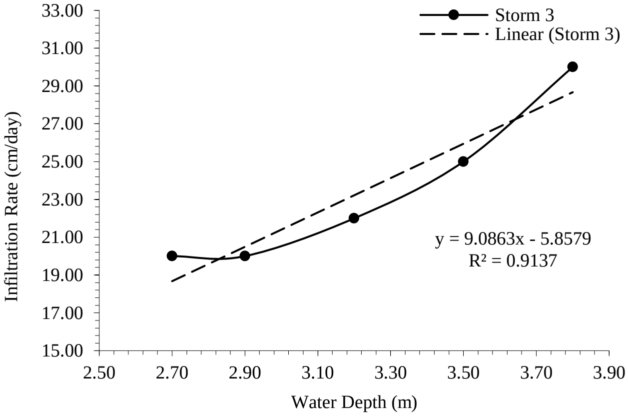


Figure 6: Correlation between the head and the infiltration rate at Waqf basin, after [3]

Asadaqa southern and northern basins were also investigated as shown in Figures 3 and 4, respectively. At storm 1, power functions were yielded as expressed in Equations 6 and 7 for southern and northern basins, respectively.

$$y = 0.38x^{3.82} \qquad (6)$$

$$y = 0.61x^{0.88} \qquad (7)$$

Similarly, power function coefficients *a* and *b* varied from storm 1 to storm 4 at Asadaqa basins, and high goodness of fit of the field data was noticed for the obtained empirical models, with r-squared = 0.94 and 0.98 at both the southern and northern basins, respectively.

However, the study [3] yielded the first-order linear relations for both southern and northern basins to describe the relation between water depth and infiltration rate, see Figures 7-(a) and (b). Thus, an increase in water depth linearly increased the infiltration rate, as expressed in Equations 4 and 5 at the southern and northern basins, respectively.

$$y = 36.528x - 32.746 \qquad (4)$$

$$y = 21.226x - 3.211 \qquad (5)$$

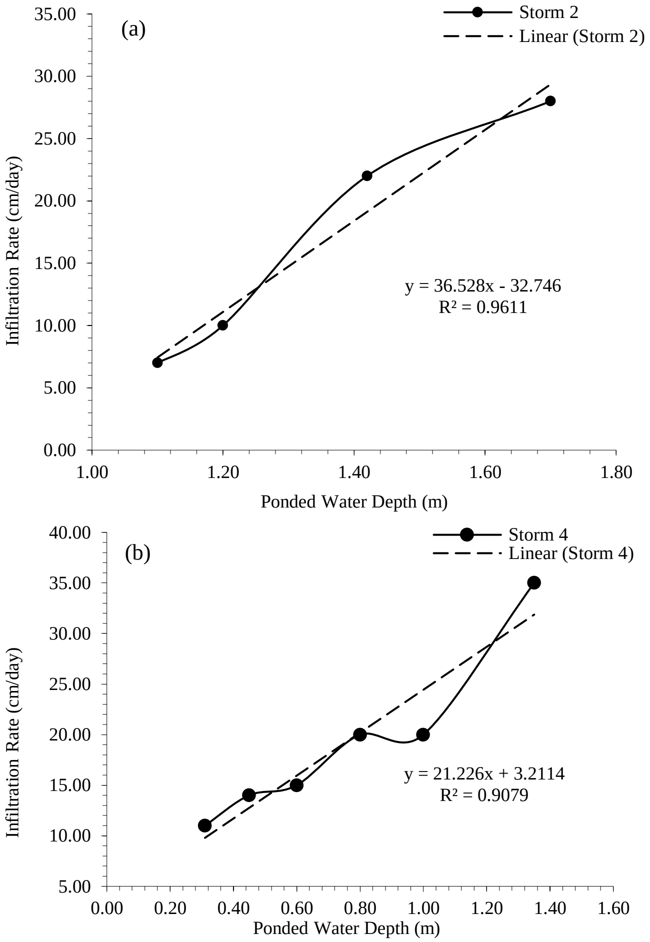


Figure 7: Correlation between the head and the infiltration rate at Asadaqa basin: southern basin(a), northern basin(b), after [3]

It was also noted that only one storm event was selected in the study [3] at the southern and northern Asadaqa basins; storm 2 and storm 4, ignoring the other storm events.

The study of Alamal basin has yielded also a power function relation as shown in Figure 5 describing the relation between the infiltration rate and the water depth, where the power function obtained at storm 1 was expressed in Equation 8 as shown in Figure 5-(a)

$$y = 0.01x^{2.50} \qquad (8)$$

Same as discussed at Waqf and Asadaqa basins, where high correctness of fit of field data was obtained at Alamal basin in this study, showing that r-squared was 0.97 for storm 1 and 0.96 for storm 2. Furthermore, the power function coefficients varied with time (from storm 1 to storm 4), and this was attributed to the siltation and biofouling of the basin floor.

However, a first-order linear relation was obtained by [3], as expressed in Equation 9 at storm 1 and shown in Figure 8-(a)

$$y = 9.5166x - 15.56 \qquad (9)$$

The same concern was noted, as only storm 2 was studied ignoring the other storm events, and it was obviously noted in Figure 8 that only three water depth readings were used to create a line of best fit and this was insufficient, to represent the relation between water depth and infiltration rate. Thus, the r-squared = 0.999 obtained was irrelevant and misleading for the actual basin status.

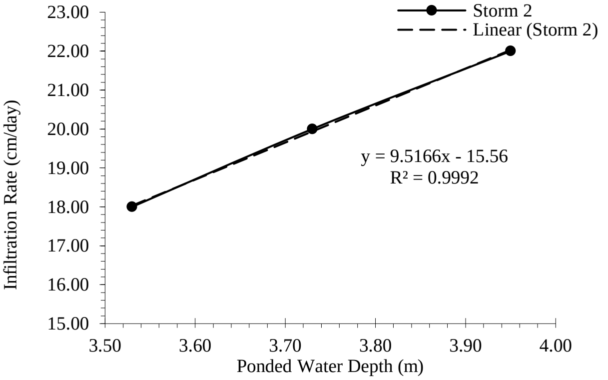


Figure 8: Correlation between the head and the infiltration rate at Alamal basin, after [3]

In this study, the power function relation between infiltration rate and water depth of the three infiltration basins revealed that the infiltration rate increased in a power function relation with the increase in the water depth. In addition, the increasing rate of infiltration rate was decreasing over time from storm 1 to storm 5, which was attributed as explained to the settling of the fine particles on the basin floor causing clogging and plugging of the system, thus degrading the basins infiltration efficiency in absorbing stormwater to the underlying soil layers.

Despite that, Bouwer stated in his study [10] that when the basin floor is clean without a clogging layer and large enough to exclude the effect of bank infiltration with a low groundwater table, increasing the water depth in the basin can thus slightly increase the infiltration rate. That can be explained by applying the Green-Ampt equation [10] for the wetting zone between the basin floor and the groundwater table. However, also [10] declared that in case the water table is high and close to the basin floor, the increase in water depth creates a remarkable increase in infiltration rate through a linear relation. Furthermore [10] also emphasized that when the ponded water depth at the basin is increased, extra pressure is induced on the bottom of the basin and thus additional compression is applied to the clogging layer which makes the clogging layer denser and more impervious.

The researcher in [11] noticed a great difference in the infiltration rate of soils with high infiltration capacity through water depths of 2.5 cm to 15 cm that was depending on the water depth. Whereas, [12] and [13] declared in their study that the infiltration rate increases direct proportionally with the increase in water depth. Figure 9 obtained by [12] shows the increase in the infiltration rate with the increase in the surface head (water depth) at the infiltration basin with a linearly proportional relation.

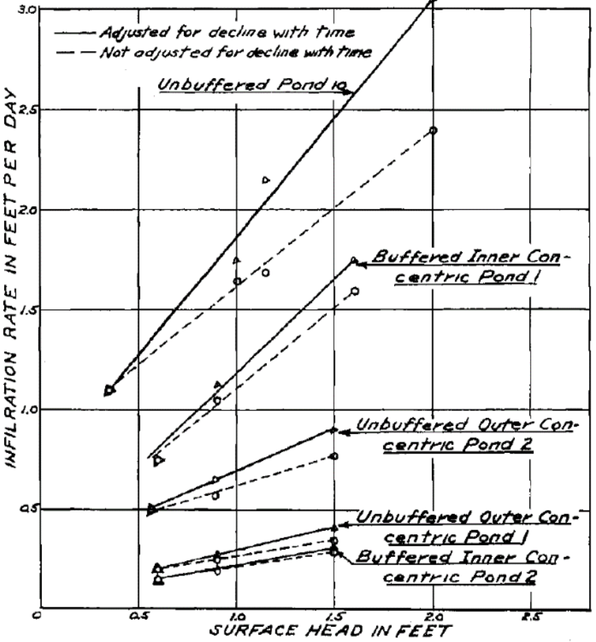


Figure 9: Increase in infiltration rate with increase in surface head, after [12]

However, [14] stated that the effect of the water head on the basin infiltration rate gradually decreases over time. The study [15], also stated that the increase in the stormwater water depth ponded in the infiltration basin can produce one of the following effects on the infiltration rate; more than linear increase, essential linear increase, less than linear increase, no increase or even a decrease in the infiltration rate. Each particular case of the effect depended on several conditions controlling the infiltration performance. Analysis of the potential cases of water depth effect on the infiltration rate showed the extent to which the effect was based on the basin in situ conditions, where the optimal water depth at the infiltration basin can only be determined by either field extermination performed in a pre-existing basin or a specific test basin. Based on [15], the shallow basins with water depths of 10 to 30 cm could be the most practical basins from the perspective of infiltration rate, since they can be cleaned and maintained easily after quick drying.

It was also shown in the study [16] that the effect of increasing the hydraulic head in the infiltration basin increases the hydraulic conductivity of the soil and thus increases the infiltration rate. The study was performed by testing two sand samples with different treatment levels and the results were obtained and shown in Figure 10.

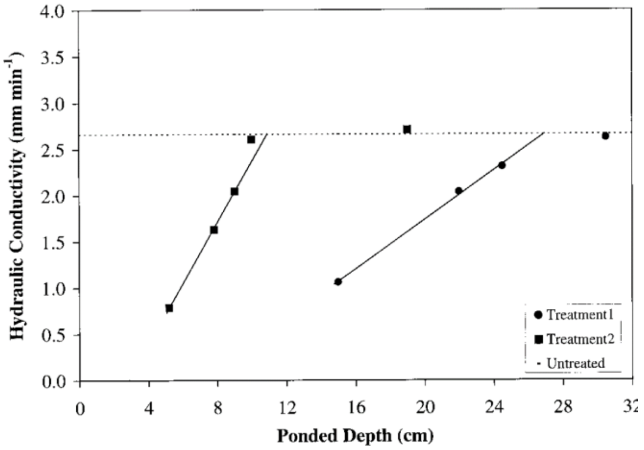


Figure 10: Relation between hydraulic conductivity and water depth for sands of two treatments, after [16]

The studies carried out to date have shown that the infiltration rate of stormwater increases with increasing water depth up to a limit after which the increase in the water depth no longer increases the infiltration rate or the infiltration rate can even decrease after a longer period. That was demonstrated when studying the three infiltration basins, where the infiltration rate improved at higher water depths similarly to the three basins, but this satisfactory improvement diminished over time and that was apparent in the decreasing infiltration rate from storm 1 to storm 5.

At Waqf basin, in early 2021, the infiltration system was significantly further developed and upgraded to improve the infiltration efficiency, which was evident when comparing readings of water depths to the infiltration rates of the past 2017–2018 rainy season and the recent 2021–2022 rainy season, where a prominent increase in the infiltration rate was obtained.

The other studied infiltration basins (Alamal and Asadaqa) were also investigated where the effect of water depth on the infiltration rate remained without significant changes as discussed in the study [1].

2. Effect of Clogging Particles

Infiltration basins are proper systems for the decentralized rainwater management system, they are widespread worldwide. However, due to topsoil clogging, infiltration basins can become unsustainable over time. As said by [17], the artificial infiltration basins should have a long service life of not less than 30 years of operation. So as to evaluate the operational efficiency and sustainability of these systems, a long-term assessment and investigatory study are necessary to perform. The main bane of the infiltration basins is the progressive problem of clogging and plugging of the basin topsoil layer due to the gradual and cumulative settling of the fine particles in the incoming collected stormwater. Clogging phenomena can occur in different shapes it could be physical, biological, or chemical clogging.

However [18] described in his study that clogging is considered the most crucial problem encountering the artificial infiltration industry in the long term. Clogging can be defined as the reduction in the porosity of the topsoil layer of the basin (sealed soil pores) due to several complicated processes of physical, chemical, and biological aspects. One of the major clogging processes is the physical one, it was defined as the high concentration of the suspended solids in the incoming stormwater such as silt, clay, sand, algae cells, microorganism cells, and other plants fragments that deposit downward to accumulate on the topsoil of the basin floor at some depths, where the topsoil layer became denser and finer forming a thin blocking layer. The thickness of this layer may vary from mm to a few cm or even more [19].

The biological clogging takes place when the bacterial flocks and algae accumulate on the basin floor, what may increase the problem is the continuous growth and reproduction of the microorganism forming biofilm and surface thick biomass layer that subsequently block the surface soil pores and prevent stormwater from imbibition [19]. However, the chemical clogging may include the precipitation of the chemicals suspended in the incoming stormwater such as gypsum, classism carbonate, phosphate, and other chemicals, the problem of chemicals may worsen due to the chemical reactions that take place under the ponded water, for instance, the pH increased due to algae consumption of dissolved carbon dioxide from ponded stormwater during the photosynthesis. In addition, Bacteria also produced gases such as methane and nitrogen during the chemical and biological processes hence blocking the topsoil pores by forming what so called a vapor barrier layer [19].

Previous field studies of stormwater recharge into groundwater aquifers supposed that physical clogging dominates over chemical and biological types [20]. Therefore, based on [21], we can hypothesize that the dominant type of clogging in stormwater infiltration systems was physical clogging.

Evidence from several previous studies indicated that the substantial impact of clogging is the immediate reduction in the intrinsic permeability of the basin topsoil layer which leads to a significant drop in the infiltration rates. Studies have shown that the cleaner the incoming stormwater quality, the longer and better the performance of the infiltration system. Figure 11 presents the reduction in the infiltration rate due to the gradual clogging over time.

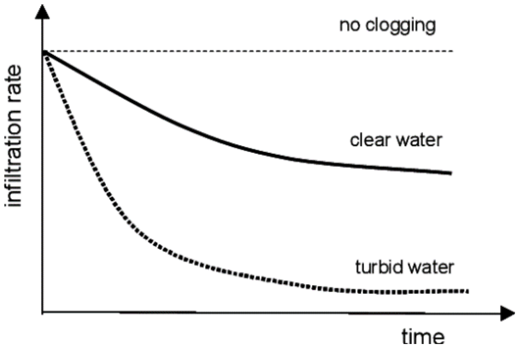


Figure 11: Conceptual graph of clogging effect on infiltration rate over time for clear and turbid water, after [18]

It can be seen in Figure 11, that as time proceeds the clogging of the basin floor is increasing with the progressive accumulation of suspended particles that perform a barrier layer between stormwater and underneath soil matrix, the layer thickness continues to increase until eventually, infiltration rates drop to severe limits such that the basin functionality was abruptly halted. The results obtained in this current study were consistent with the previous studies highlighted in the section of the clogging effect.

The infiltration efficiency in the first storm event was better than in subsequent storms, that was due to the progressive accumulation of suspended particles that settled on the bottom of the infiltration basin, preventing stormwater from penetrating the soil surface and percolating to the underlying soil layers. Figure 12 shows the influence of the time span and the storm number on the infiltration rate at Waqf basin.

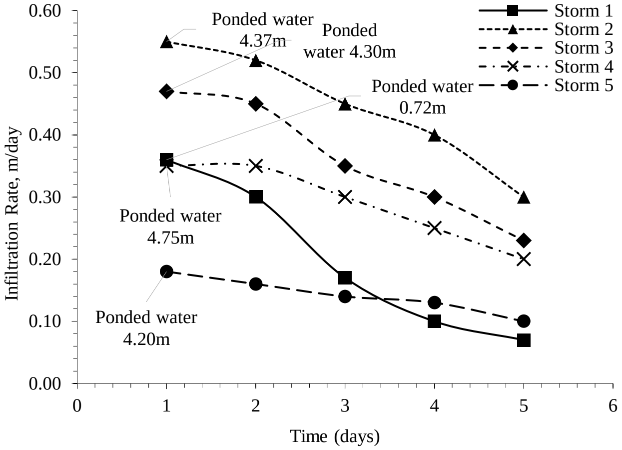


Figure 12: Infiltration rate within 5 storms at Waqf basin

Figure 13 shows the corresponding power function relation presenting the decrease in the infiltration rate over time for the five storm events. It was found that each storm event has its specific relation since the clogging intensity varies over time. But in general, the degrading of the performance has the same shape and rate of decrease over time, as shown in Figure 13.

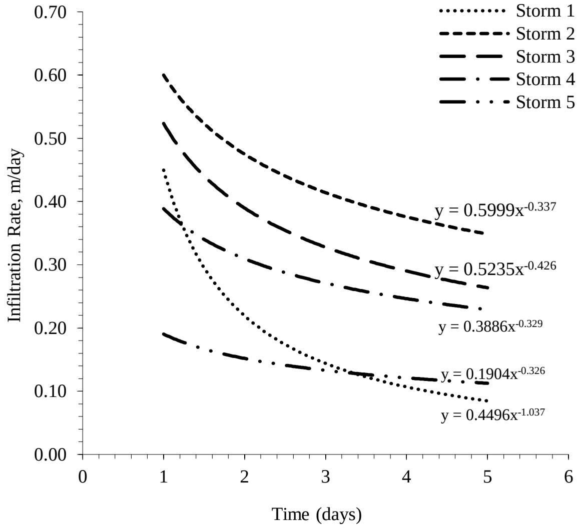


Figure 13: Decrease in infiltration rate over time at Waqf basin

The decrease in the infiltration rate during the 2021-2022 rainy season was attributed to the clogging effect of suspended particles conveyed into the infiltration basin with the inflowing stormwater as discussed before. Furthermore, storm 1 may flush and wash out the urban areas including the roads and unpaved areas that may carry a large amount of clogging particles to the basin hence reducing significantly the infiltration rate. The reduction in infiltration rate was relevant to Figure 11, which provided a conceptual representation of the behavior of infiltration rate over time. This means that the more suspended particles were brought to the infiltration basin, the faster the system will clog and fail.

Figure 13 also shows that the reduction in the infiltration rate also occurred while recording water depth readings after each storm event plotted on the x-axis. A further reduction occurred due to system clogging as noticed from storm 1 to storm 5. Power functions by best fitting regression were created as seen in Figure 13. Storm 2's infiltration rate was higher than Storm 1's due to the water depth of 4.37 m. However, the ponded water depth was 4.20 m for storm 5 but with a lower infiltration rate due to clogging problems over time.

Figure 14 shows the same influence occurring in the southern Asadaqa basin, the reduction in the infiltration rate was also occurring over time and was affected by the water depth of stormwater. Ponded water depth at the basin showed a decline in the infiltration rate from storm 1 to storm 4 due to the clogging problem. This was obvious because the ponded water depths were the same across the four storms, despite different rates of infiltration being produced.

At Asadaqa southern basin, the reduction in the infiltration rate was similarly presented by power functions that were created at each storm as shown in Figure 15.

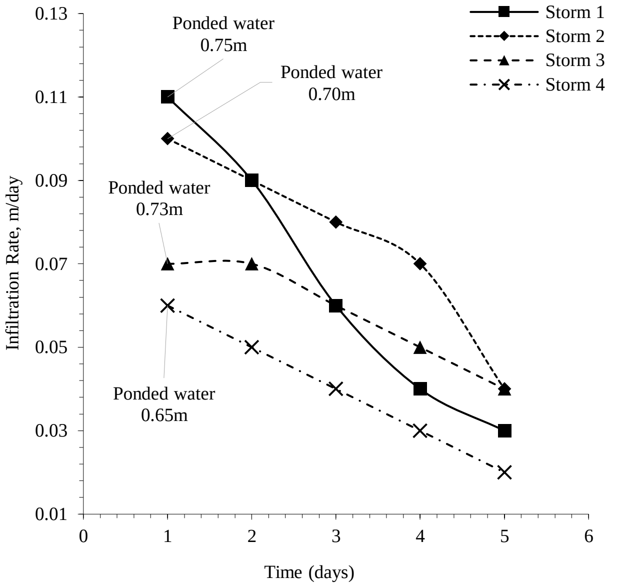


Figure 14: Infiltration Rate Within 5 Storms at Asadaqa-South Basin

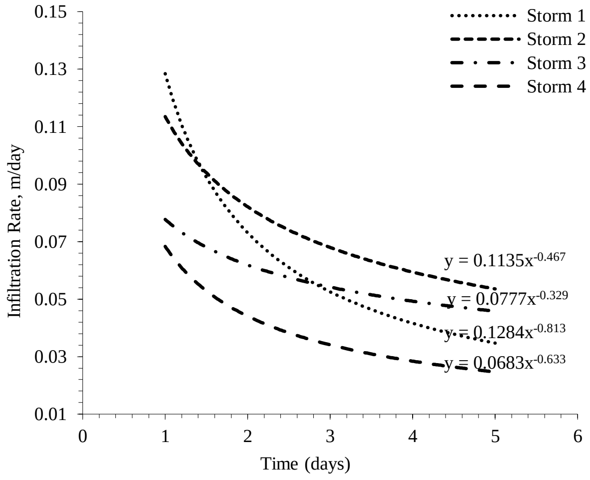


Figure 15: Decrease in infiltration rate over time at Asadaqa southern basin

At the northern Asadaqa basin, Figure 16 shows that the infiltration rate at storm 3 was higher than of storm 1, which was due to the higher water depth at storm 3 reaching 0.47 m, while during storm 1 it was only 0.25 m. The reduction in the infiltration rate over time was expressed as a power function as shown in Figure 17.

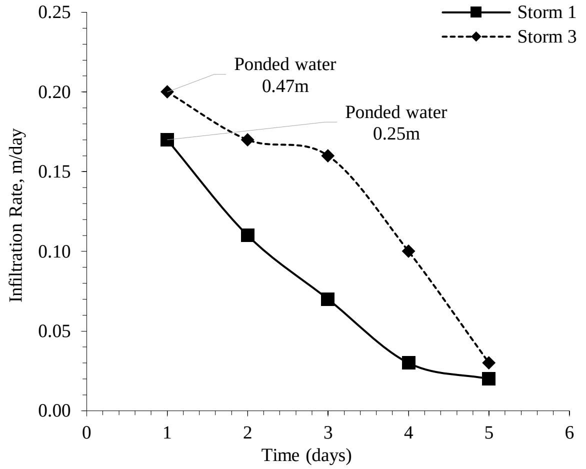


Figure 16: Infiltration rate within 5 storms at Asadaqa northern basin

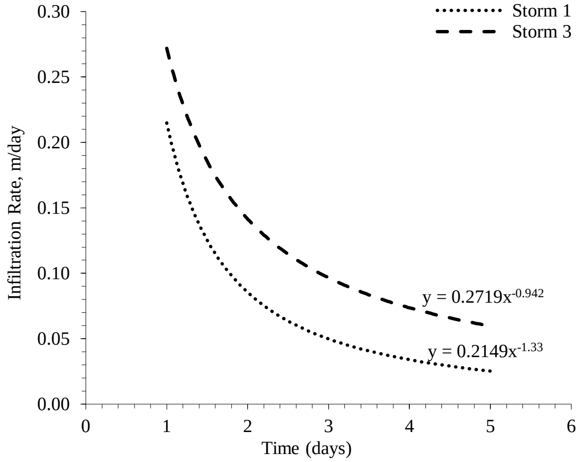


Figure 17: Decrease in infiltration rate over time at Asadaqa northern basin

It was noteworthy that the readings of ponded water depths were obtained for only two storms (1 and 3), the other storm events did not generate a considerable height of ponded water to be measured at the northern Asadaqa basin as shown in Figure 17.

At Alamal basin, Figure 18 showed that the infiltration rate decreased over time and each increase in water depth increases the infiltration rate to a certain limit in a power function relationship at an early stage of a storm event. However, the infiltration rate dropped from storm 1 to storm 4 due to the clogging problem. Although storm 3 was not an earlier event, it has the highest infiltration rate owing to the high water depth of 7.5 m.

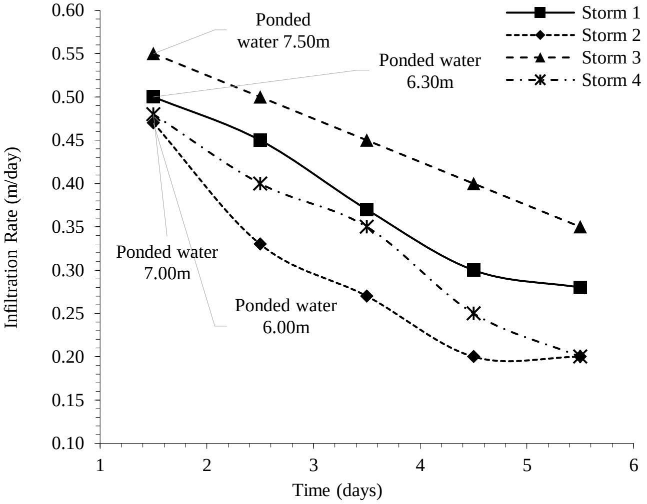


Figure 18: Infiltration rate within 5 storms at Alamal basin

Figure 19 showed that the infiltration rate at Alamal basin exhibited the same behavior as the other infiltration basins where the decrease in infiltration rate was correlated with time as a power function representing a decrease in infiltration rate due to the clogging problem previously mentioned in this study. The following sections will examine the analysis of sediment composition, which has emphasized that physical clogging of silt and clay in the stormwater infiltration systems was seriously the dominant.

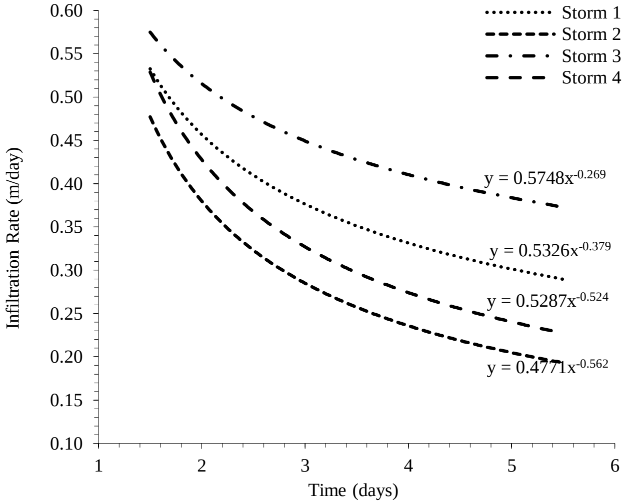


Figure 19: Decrease in infiltration rate over time at Alamal basin

3. Comparison of Three Basins

It was obviously found that the ponded water depth influences the infiltration rate; increasing the water depth increases the infiltration rate due to the increase of water pressure on the bottom of the basin, which compresses rainwater to seep through the top layer of soil. Furthermore, the infiltration rate was also affected by the storm number, with the earlier storm events that developed an acceptable infiltration performance for the three basins as the bottoms of the basins were clean and no sediments or accumulated particulate matter was yet present. In addition, the infiltration rate was also different between the three basins, which was due to the different soil profiles under each basin's bottom and the different infiltration techniques used.

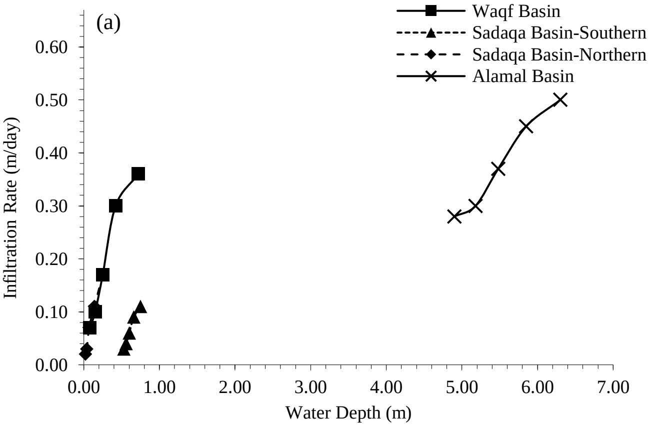
Waqf Basin has performed better with an infiltration rate of more than 50 cm/day during certain storm events in the 2021-2022 rainy season, higher than the old rates before the second phase of upgrade and development works, which barely reached 30 cm/day. The increased rate of infiltration at Waqf Basin was attributed to the 18 newly drilled wells (dry wells) discussed in the previous sections which have significantly increased the basin infiltration rate. The novel technique applied at Waqf basin has demonstrated an improvement in the infiltration rate, which previously ranged only between 0.05 and 0.3 m/day.

The infiltration rate at the southern and northern Asadaqa basins ranged from 0.05 to 0.20 m/day and was accepted for shallow water depths, However, at higher water levels, the rate of infiltration increased significantly due to the combined system of surface spreading and drywells (boreholes) penetrating the vadose zone and accelerating the stormwater infiltration into the aquifer. It was also noted that the old infiltration rates of the 2017-2018 wet season were not massively altered compared to the 2021-2022 rainy season; thus, the system functioned with no changes.

At Alamal basin, the infiltration rate increased with increasing water depth, as discussed in previous sections, and ranged from 20 to 55 cm/day according to stormwater depths. Although the bottom of Alamal basin has a low hydraulic conductivity of about 0.89 m/day [22], the high rate of infiltration was attributed to the high water depth of 7.0 m, which induced high pressure on the basin bottom. The improvement in recent infiltration rates (obtained in the 2021-2022 wet season) was attributed to repair, maintenance, and remedial measures in the basin bottom, such as drying, scraping, plowing, and disking or replacing the thick restrictive top layer (cake layer) to improve the soil sorptivity.

Figure 20 shows the infiltration rate versus the ponded water depth of the three basins superimposed in a graph at specific storm events.

Figure 21 shows the changes in the infiltration rate over time for the three infiltration basins at specific storm events superimposed in a graph.



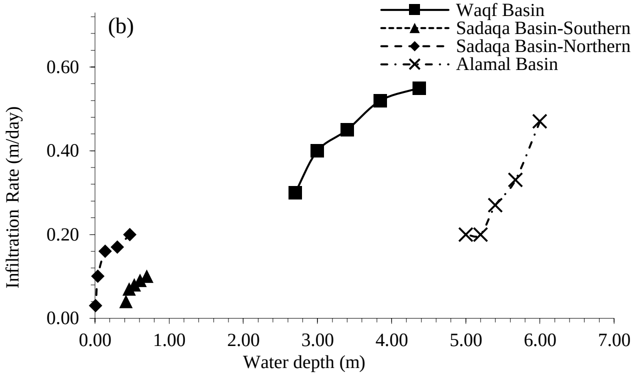


Figure 20: Relation of water depth with infiltration rate for three basins: storm1 (a), strom2 (b)

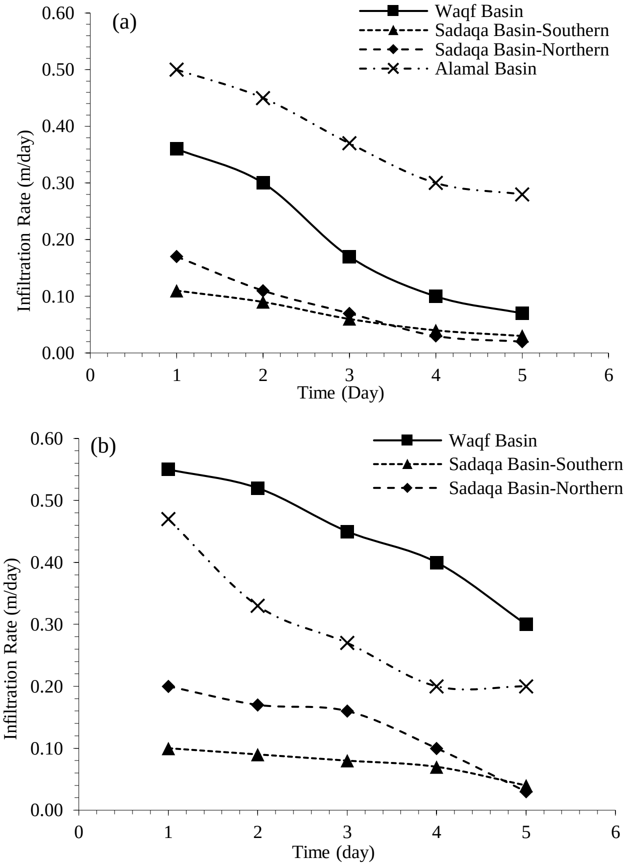


Figure 21: Infiltration rate of three basins over time: storm1 (a), strom2 (b)

4. Analysis of Clogging Sediment at Waqf Basin

Waqf basin was studied in this regard to expose the composition and proportion of the suspended solids in the collected stormwater. The sediment samples were collected after a storm event occurred on 15/01/2022, the water depth in the basin was 5.5 m and the rainfall depth was 27.3 mm, based on records from the Ministry of Agriculture. On 01/23/2022 a field visit was conducted to Waqf Basin to collect the first set of samples (mid-season samples) for the settled sediment at 4 pre-selected locations (L_1, L_2, L_3, L_4) distributed along the length of the basin. Figure 22 shows the four sample locations (one sample was collected from each location) and Table 2 shows the samples' notations.

Figure 22: Layout of Waqf basin and sample's location

Table 2: Notation of Sediments Samples

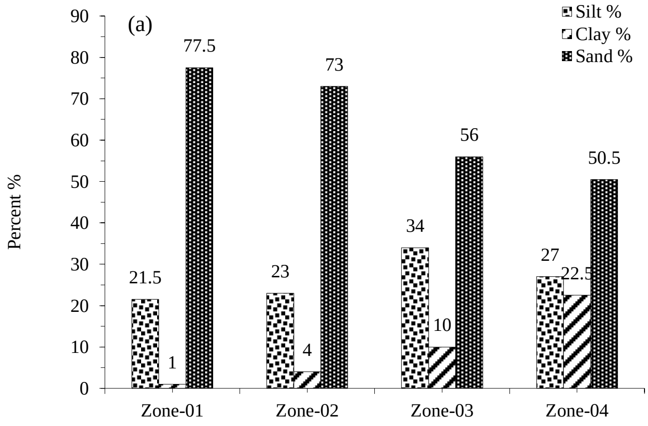
Lo.	Zone	Code	Testing Type	Latitude	Longitude	Weig ht, g
L_1	Zone-01	L_1-S_4	Sedi- ment	31°30'0.72"N	34°27'34.36"E	500
L_2	Zone-02	L_2-S_4		31°30'1.27"N	34°27'33.06"E	
L_3	Zone-03	L_3-S_4		31°30'2.06"N	34°27'31.53"E	
L_4	Zone-04	L_4-S_4		31°30'2.94"N	34°27'30.15"E	

The Environment Quality Authority (EQA) laboratory in the Gaza strip was chosen to carry out the required testing, with the laboratory being able to provide accurate results using newly installed testing machines with the necessary experts and qualified team. Mid-season sediment samples were collected at a distance of 1.0 m from the south bank of the basin and packed in plastic bags of 500 g each. Table 3 shows the results of the sediment analysis.

Table 3: Results of Sediment Analysis at Mid-season of 2021-2022 (Waqf Basin)

Zone	Code	Classification, Texture Triangle	Silt%	Clay %	Sand %
Zone-01	L_1-S_4	Loam Sand	21.5	1.0	77.5
Zone-02	L_2-S_4	Sandy Loam	23.0	4.0	73.0
Zone-03	L_3-S_4	Sandy Loam	34.0	10.0	56.0
Zone-04	L_4-S_4	Clay Loam	27.0	22.5	50.5

Analysis of the sediment composition has revealed that the amount of sand (diameter greater than 0.05 mm) decreases from zone 1(zone 1 is close to the inflow point) to zone 4 as shown in Figure 23, and this has been attributed to the high settleability of sand particles, which settle and accumulate near the inlet (Zone 1) in a shorter time.



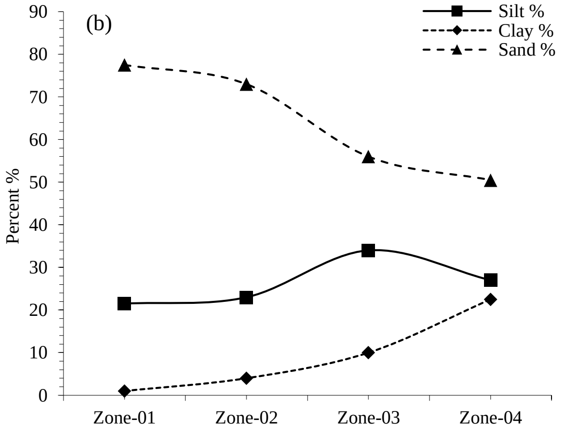


Figure 23: Sediment analysis of samples at mid-season of 2021-2022 (Waqf basin): percent bar chart (a), curves (b)

In contrast, the amount of silt (0.05 to 0.002 mm) and clay (less than 0.002 mm) increased in the sediment from zone 1 to zone 4 as both take a longer period to settle and deposit at the bottom of the basin, that explain the high content of silt and clay in the sediment composition at zones 3 and 4. This helped locate the 18 drywells (boreholes) drilled at the west end of the basin (zone 4) to ensure the best location to protect the system from rapid clogging and failure. Zone 4 is far better suited to receiving higher quality stormwater for groundwater recharge as it takes a longer time for stormwater to flow and reach this zone west of the basin, settling all heavy suspended matter including silt and clay.

Another set of samples was taken from the sediment at the bottom of Waqf basin to study the composition of the sediment settled at the end of the 2021-2022 rainy season, where a field visit was conducted on 21/06/2022 for samples collection as seen in Figure 24 to reanalyze and study the sediment composition. The samples were taken from the basin's bottom sediment in the middle of each zone (from zone 1 to zone 4), then placed in plastic bags (500 g) and shipped to the lab for testing.

Figure 24: Collection of sediment samples at end-season (dry basin)

The test results of the sediment samples were obtained from the EQA laboratory and summarized in Table 4.

Table 4: Results of Sediment Analysis at End of 2021-2022 Season (Waqf Basin)

Zone	Code	Classification, Texture Triangle	Silt%	Clay %	Sand %
Zone-01	L_1-S_5	Sandy Loam	23.0	9.0	68.0
Zone-02	L_2-S_5	Sandy Loam	25.0	13.5	61.5
Zone-03	L_3-S_5	Sandy Loam	27.0	18.0	55.0
Zone-04	L_4-S_5	Loam	30.8	23.3	45.9

End of season results has shown a significant increase in the accumulated sediment at the bottom of Waqf basin, with the percentage of clay, silt, and sand similar to mid-season.

However, a large difference in the quantity of clay and silt was observed in zones 3 and 4, significantly more so than in zones 1 and 2. Figure 25 shows the sediment composition at the end of the wet season for each zone.

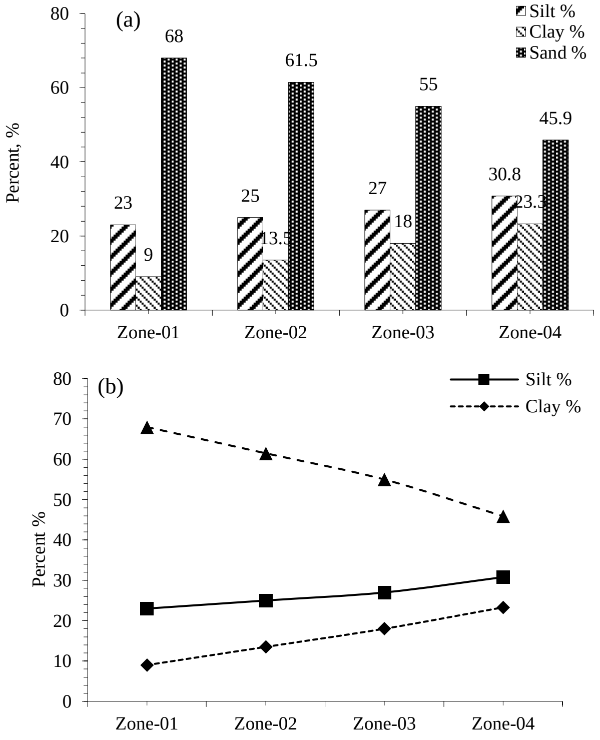


Figure 25: Sediment analysis for end-season 2021-2022 samples at Waqf basin: percent bar chart (a), curves (b)

The results also showed that the larger amounts of sedimented clay and silt occurred in zones 3 and 4, which was due to the existence of the 18 drilled recharging boreholes that functioned as water drainage points, sending the stormwater into the ground and thus directing the flow pattern from east to west towards the boreholes in zone 4. This transported a larger amount of suspended matter, including silt and clay, to zone 3 and then to zone 4 successively.

In addition, the thickness of the sediment layer (dry dense layer) was also measured in the field, where three tape measured locations were taken at each zone. The distance between each measurement was 10 m, then the mean thickness of the sediment layer was estimated for each zone when the basin was dry. Table 5 shows the obtained results of layer sediment thickness at Waqf basin.

Table 5: Sediment Thickness at Waqf Basin

Zone	Sediment Thickness, cm			
	Reading 1	Reading 2	Reading 3	Average
Zone-01	3.8	3.5	3.0	3.43
Zone-02	3.9	3.7	4.0	3.87
Zone-03	4.2	4.0	3.5	3.90
Zone-04	4.2	4.3	4.0	4.17

In Figure 26, we notice the increase in the thickness of the sediment layer from zone 1 to zone 4, the average thickness of the sediment layer at zone 1 was 3.43 cm, while the average thickness at zone 4 was 4.17 cm, with an increase in thickness of 0.74 cm. Similarly, the increase in sediment layer thickness was attributed to the direction of stormwater flow towards the 18 drilled boreholes. Thus, all suspended matter such as silt and clay are deposited around the boreholes in zone 4, where stormwater enters the groundwater through the gabions of the boreholes, leaving the silt and clay deposited on the basin floor.

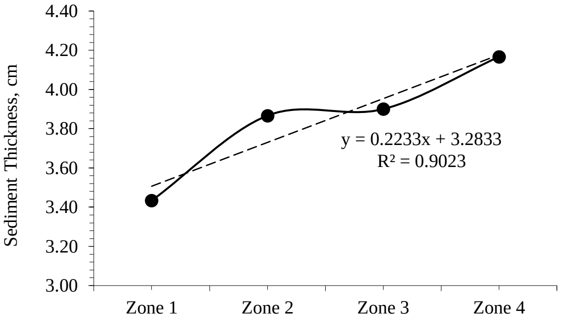


Figure 26: Thickness of sediment layer at Waqf basin (dry basin)

V. CONCLUSION

Stormwater infiltration technology is the most essential solution to improve the quality and quantity of the Gaza strip aquifer. Through this study, the factors influencing the infiltration rate were studied and investigated at three existing main infiltration basins (Waqf, Sadaqa, and Alamal).

In all cases, the infiltration rate was affected by the water depth of stormwater, with an increase in water level leading to an increase in the infiltration rate up to a certain limit at which water depth no longer increases the infiltration rate. The relation between the water depth and the infiltration rate was a power function and not linearly proportional as in some previous studies.

The infiltration rate was also affected by the amount of suspended solids which is considered the “bottleneck” of any artificial infiltration system, since the fine particles can make seasonal clogging and blocking of the topsoil layer, impeding water seepage downwards. The clogging materials come with rainwater from roads and farmland; Therefore, a sand trap and retention basin are essential to settle the particles and other suspended matter before they flow into the infiltration basin, this should protect the system from clogging risks and extend the basin lifespan. At Waqf basin, the infiltration rate was improved by drilling 18 boreholes (dry wells) that reached 55 cm/day at 4.95 m water depth at this present wet season, in the past wet season it reached almost 30 cm/day at the same water depth, this can underline the significant influence of the drilled boreholes, which can accelerate the penetration of rainwater into the groundwater by bypassing the soil layers of low permeability.

As a future recommendation, additional development work should be carried out in Waqf basin by adding mesh materials (non-woven geotextile) between the four zones and adding a new series of boreholes (dry wells) in zone 3 that will highly improve the infiltration rate at Waqf basin. The sediment layer at Waqf basin was tested and analyzed at both mid and end of the 2021-2022 rainy season, the results showed that silt and clay were dominants as physical clogging components where they increased from zone 1 to zone 4 and increased from the mid-season to the end-season. The thickness of the sediment layer at Waqf basin was measured and the results revealed an increase in the thickness from zone 1 to zone 4, where the 18 drilled boreholes functioned as drain traps sending the stormwater into the groundwater.

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