Enhancement of the Efficiency of Infiltration Basins for Effluent Recharge

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Abstract

The Gaza Strip suffers from high pressure imposed on its water resources. There is a deficit of about 50 MCM (million cubic meters) every year, which has led to a declination of groundwater level and deterioration of groundwater quality. The Agricultural sector in the Gaza Strip consumes around 75-80 MCM of water annually. Water used for this purpose comes mainly from groundwater wells. New water resources are sought to fulfill the water deficit; among them is the artificial recharge of treated wastewater to groundwater by the mean of spreading basins. Recovery of the infiltrated treated wastewater is envisaged as a mean to support the agricultural sector in Gaza. In order to investigate the performance of the infiltration system in terms of quantity and quality, field experiments were performed. In addition to that, modeling of the unsaturated zone using theGreen-Ampt model (1911) was performed in order to predict the existing andenhanced infiltration rate. The results showed that the infiltration rate is affectedby the soil type, and its permeability, also with the quality of the effluent water to the basin. Removing the upper 2.0 meters of soil layer at IB1 and replacing it with new sand martial with high permeability introduced an efficient solution for the enhancement of the infiltration rate. Also penetrating the lower soil layers with 60 piles and filling the piles with gravel fine media with high permeability will increase the infiltration rate for whole of the basin according to the study.Performing 35 cycles of wetting and drying during the year with 2 days of wetting in summer and winter and 7 days of drying in summer and 12 days of drying in winter, will help to reach the optimal infiltration rate. Soil plowing after each drying cycle for the basin will maintain good infiltration rate and prevent accumulation of the organic matter (OM) in the top soil layer.

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1   Introduction

The Gaza Strip suffers from high pressure imposed on its water resources. There is a deficit of about 50 MCM (million cubic meters) every year, which has led to a declination of groundwater level and deterioration of groundwater quality. New water resources are sought to fulfill the water deficit; among them is the artificial recharge of treated wastewater to groundwater [1].

Artificial recharge is one means of conserving water by allowing storage and future use of reclaimed water [2]. Artificial recharge and water reuse are important aspects of integrated water management where water resources management problems are solved by considering all aspects [3]. Thus moving towards attaining sustainable water management in addition, artificial recharge can significantly contribute to water quality improvement by natural attenuation of contaminants via passage of the water through the aquifer. The ability to obtain an improvement in water quality would be a major benefit of artificial recharge in less arid parts of the world where water scarcity and quality issues are prevalent [2].

Wastewater reuse is envisaged primarily as a source to support the agricultural sector in Gaza [4]. Upon the fact that the entire existing agricultural water demand is taken from the groundwater aquifer, of which a large proportion is brackish, Palestinian Water Authority (PWA) addressed that the long-term target is that only minimal fresh water will be provided for soil flushing and specific high value crops. Other low quality water and conservation practices, including brackish water, storm water harvest, blending of water and conjunctive use of saline and non-saline water, will be utilized to optimal economic and practical effect in accordance with the following targets. Ultimately, by 2020 the utilization of wastewater is planned to provide 50 % of the total required by agriculture [5].One of the artificial recharge methods is infiltration to unconfined aquifers via pond infiltration or surface spreading[2]. Recharging basins are still the most common method of recharge and provide excellent versatility for water resources planning[6]. Optimum performance of artificial recharge system depend entirely on local conditions of soil, hydrogeology, topography, water availability (quality, continuous, or interrupted supply), and climate [7].

Because infiltration capacity is rapidly reduced due to silting, chemical precipitation, and accumulation of organic matter; maintenance of artificial recharge structures is considered essential [8]. As the problem of the artificial recharge is the reduction of infiltration capacity in the infiltration basins; this paper investigate ways to enhance the efficiency of Infiltration Basins for effluent recharge.

2   Materials and Methods

2.1 Study Area

The coastal region, Gaza Strip, is a semi-arid coastal land of roughly 240 km^2 of arable land along the eastern Mediterranean Sea. The total area is about 365 km^2. It has an average maximum length of 45 km between the boundary near Beit Hanoun in the north, and Rafah on the Palestinian Egyptian border in the south, Figure 1. Its width varies from 6 km along the line transversing through Deir El-Balah in the center, to 13 km along the Palestinian Egyptian boundary in the south [9]. The Gaza Strip is located between

longitudes 34° 2" and 34° 25"east, and latitudes 31° 16" and 31° 45" north [11].

Figure 1: Map of the Gaza Strip [10]

The site is located east of Gaza City, next to the border with Israel. The site is located on a slope with the eastern part elevated at 70 meters above sea level (masl) and the western part at 50 masl, Figure 2. The land has previously been used for agriculture. The areas north and south of the site are used for orchards and along the western side a cemetery is located [12].

Figure 2: Location of the Site

2.2 Data Collection

2.2.1 Soil Classification Tests

The location of bore holes (5 bore holes) was selected as shown in Figure 3, after continuous monitoring for the infiltration basin (IB 1), at the places which has low infiltration rate.
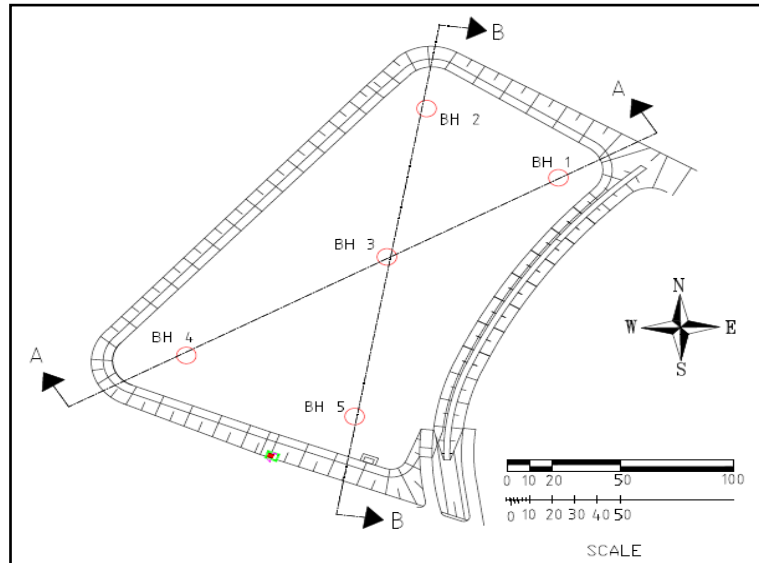

Figuer 3: Location of Bore Holes

The bore holes was performed by the drilling method using Rotary Auger. disturbed samples were collected each 30cm until the depth 2.10m and each 1.0 m until the depth of 12.0m (end of bore hole), with a total of 17 samples for each bore hole. Samples were selected in a way representative to the soil strata within the borehole along the depth of 12m for the infiltration basin (IB1).

2.2.2 Soil Quality Tests

Soil quality tests was conducted in order to check if soil contains high load of organic matter (OM) and high rate of sodium adsorption ratio (SAR). The samples from the same bore holes was taken in parallel with the soil classification samples each 30cm until the depth of 2.10m (7 samples from each bore hole).

2.2.3 Water Quality Tests

Quality of the effluent (partially treated wastewater) was tested in order to determine the parameters: Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Total Suspended Solids (TSS), and Total Coliform (TC).

2.2.4 Modeling the Unsaturated Zone

Modeling for the unsaturated zone and its applicability in the field of infiltration basins by using the Green–Ampt Infiltration model (1911).

3   Results and Discussion

3.1 Results of Soil Classification Tests

The bore holes indicated that the soil strata in the infiltration basin IB1 consists the following layers (soil types):

- Sand:is a poorly graded Sand, dim yellowish with little gravel (Kurkar) exist at variable depths as indicated in Figure 4 and Figure5. It contains (85%-100%) Sand, (1%-19%) % gravel, and a little fines contents (0%-15%). The layer is non-plastic and has good permeability characteristics.
- Clayey Sand:is a poorly graded Clayey Sand, Slightly light brown with little gravel (Kurkar) exist at variable depths as indicated in Figure 4, and Figure 5. The layer is of low to medium plasticity, contains (3%-10%) gravel, (60%-85%) sand, and (15%-40%) fines. This layer is of low permeability.
- Sandy Silty Clay: is well graded sandy silty clay, dark brown with little gravel (kurkar). The layer is of medium plasticity, and contains (3%) gravel, (1-33%) sand, (12%-28%) silt, and (16%) clay. This layer is of low permeability as shown in Figure 4, and Figure 5.

According to Taylor & Ashcroft, 1972 [13] sandy soils have the highest infiltration rates and clayey soils have the lowest infiltration rates.

3.2 Permeability Test Results for the Bore Holes from (1-5)

The hydraulic conductivity K was estimated according to Hazen equation [14],

$K = Cd_{10}^2$,

Where;

K : is the saturated hydraulic conductivity,

C : is a conversion coefficient, and

d_{10} : is the grain size for which 10% of the sample is more fine (10% of the soil particles have grain diameters smaller than d_{10}). For Ks in units of cm/s and for d_{10} in units of mm, the coefficient, C, is approximately (1).   Figure 6 shows the variation ofhydraulic conductivity K according to the soil depth at bore holes from (1-5).

3.3 Results of Soil Quality Tests

3.3.1 Organic Matter Test Results

Organic matter (OM) in the top soil layer is the main factor determining treated waste water (TWW) infiltration into the soil. Soil plowing reduces OM content in the top soil layer and consequently, reduces the effect of OM on the soil hydraulic properties. Soil plowing was found to be an efficient procedure that can be employed to reduce OM content in the top layer and maintain high infiltration rates of TWW into the soil [16]. Figure 7 shows the variation of OM with depth for the bore holes from (1-5).
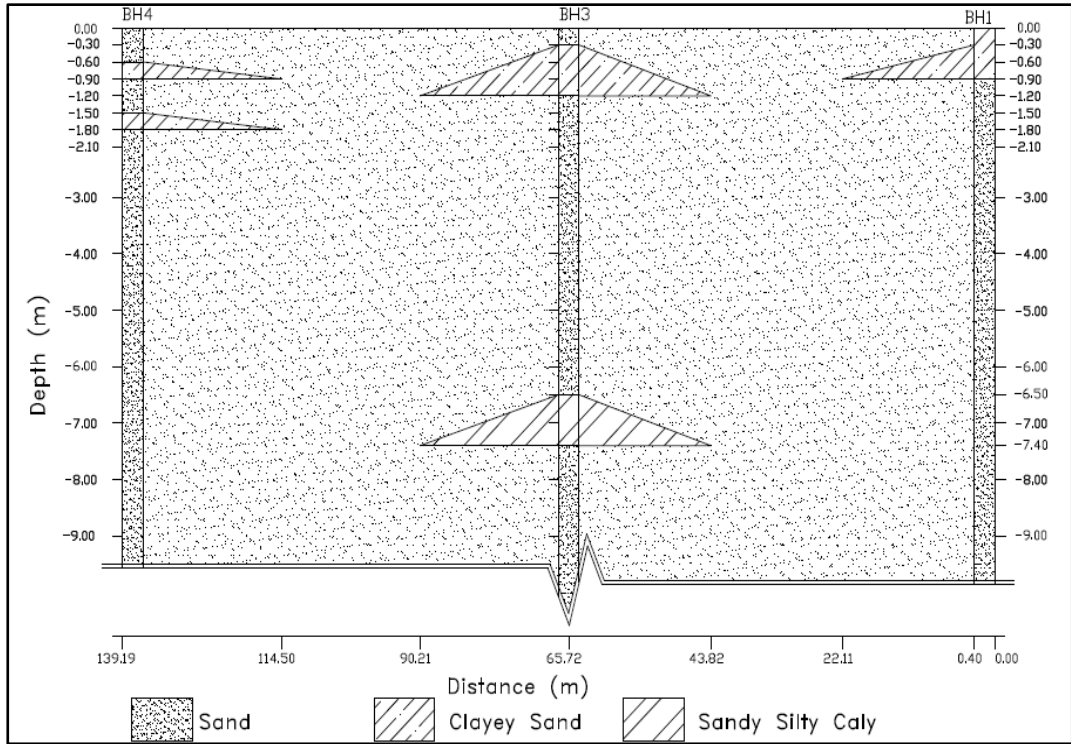
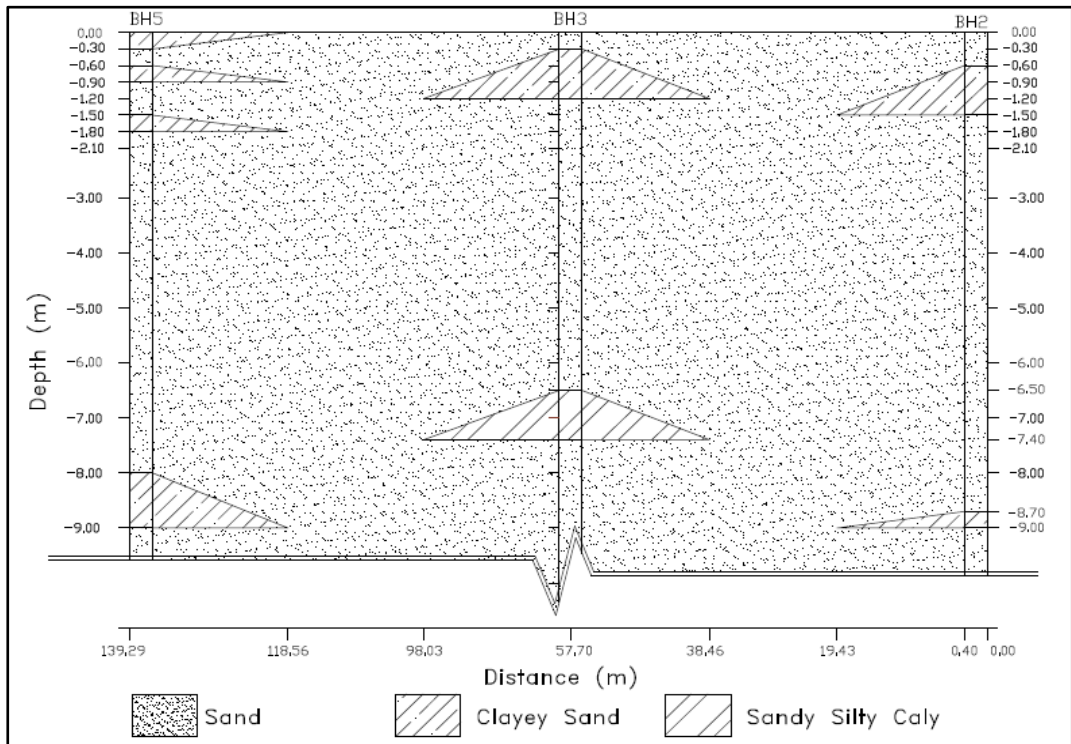Figure 4: Geological Cross Section A-A (BH1-BH3-BH4)

Figure 5: Geological Cross Section B-B (BH2-BH3-BH5)

3.3.2 SAR Test Results

Sodium Adsorption Ratio (SAR) test results in Table 1 show that the rate of SAR is less than 13 in all the tested boreholes, which means that the soil physical condition is normal [17]. Accordingly SAR will not affect the infiltration rate.

Table 1: SAR Test Results

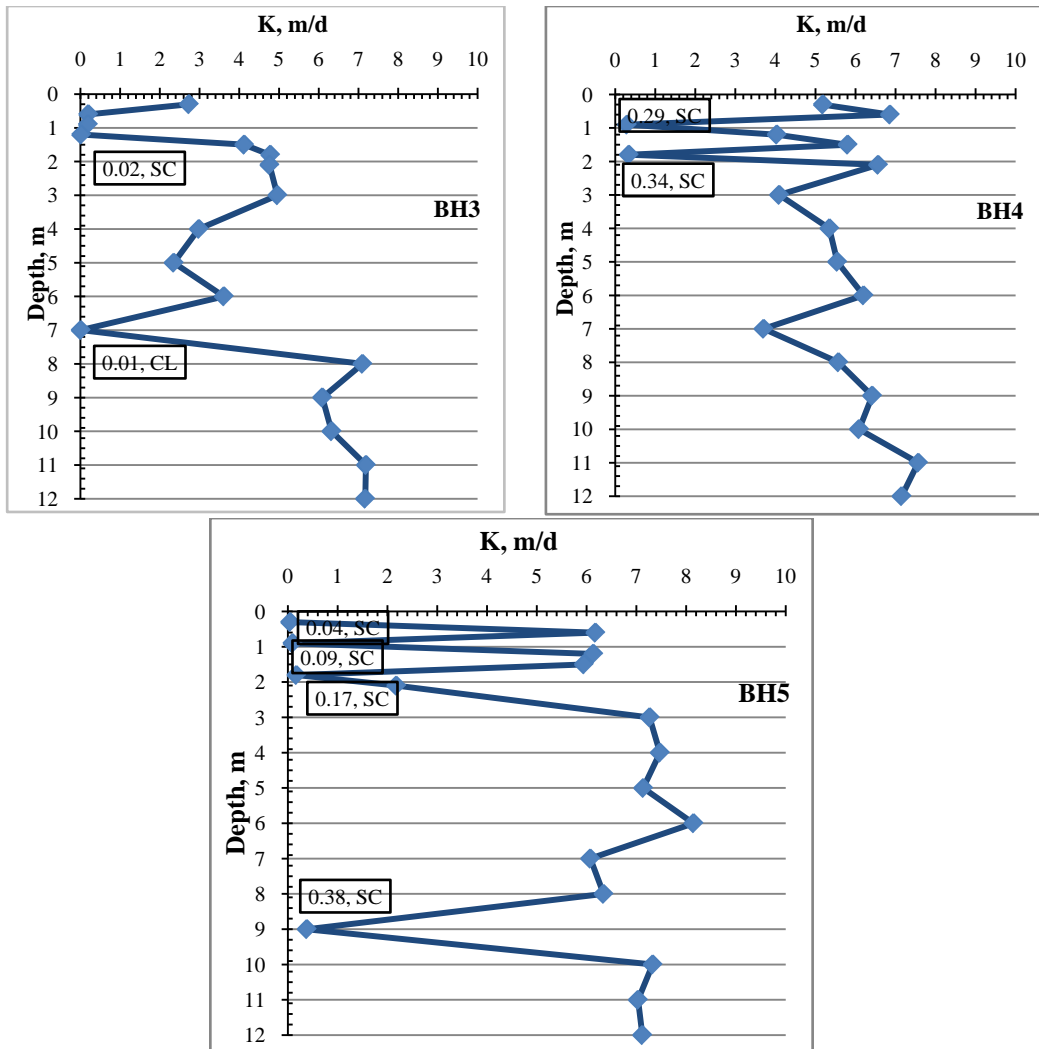| Depth	SAR				
(m)	BH1	BH2	BH3	BH4	BH5
0.3	1.64	0.67	0.99	0.55	1.26
0.6	0.96	0.54	0.76	0.53	0.46
0.9	0.97	0.97	0.86	0.52	0.82
1.2	0.97	0.95	1.20	0.48	0.97
1.5	0.50	0.93	0.69	0.33	0.38
1.8	-	0.59	0.51	0.36	0.76
2.1	0.34	0.49	0.61	0.32	0.78
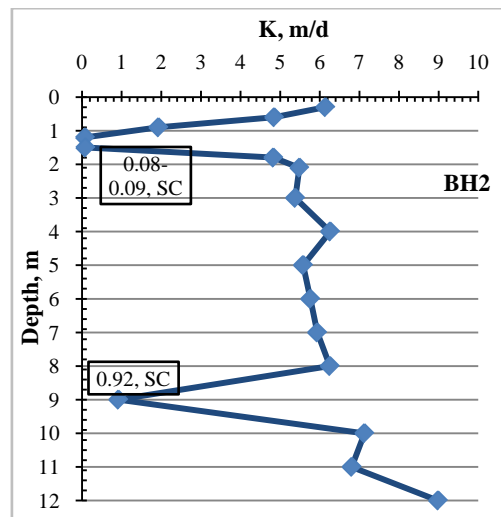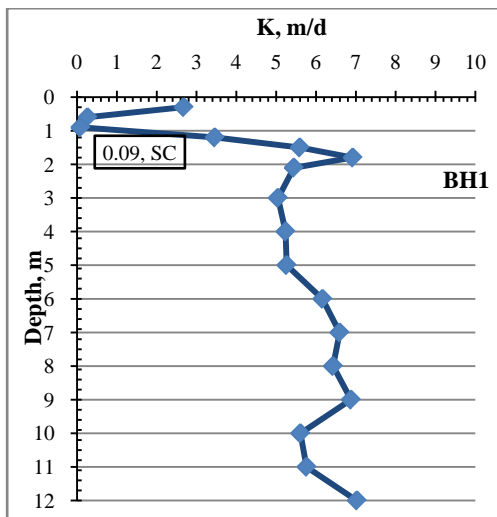
Figure 6: Variation of HC (K) According to Soil Depth for Bore Holes (1-5)
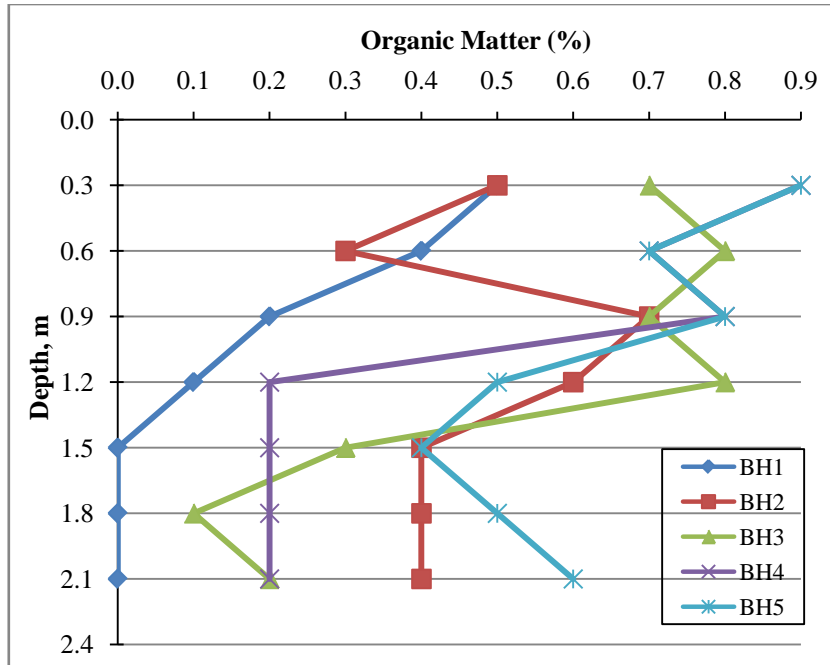
Figure 7: Variation of OM with Depth for All Bore Holes (1-5)

3.4 Results of Water Quality Tests

Table 2 shows the historical records of influent water quality to IB1, for the period from 30.06.2013 to 24.07.2013 (grab samples were taken).

Table 2: Water Quality Tests Results

Location	BOD (mg/l)	COD (mg/l)	TSS (mg/l)	TC (n/100ml)
IB1	100	320	78	120

According to the design criteria [10], the BOD concentration is still out of range (much higher than the design criteria for effluent recharge which is 10-20mg/l), and accordingly; the BOD and COD concentration are not suitable for the infiltration purposes.The design criteria for suspended solids ranged 15-20mg/l. The TSS concentration for the existing effluent discharged to the basins is much higher than the design criteria. Accordingly, the TSS concentration is not suitable for the infiltration process. According to the design; Fecal coliform (FC) should be <200 No/100, the test results showing good value for infiltration since TC is less than the design criteria for FC. Historical utilization of infiltration basins for partially treated effluent with high TSS might have been the reason for diminishing the infiltration capacity of the top soil layer of the basin.

4   Modeling the Unsaturated Zone

A large number of infiltration models, including the Green-Ampt model, the Richards equation, the Kostiakov model, the Horton model, and the Philip model have been developed in the last century.The formulation of the Green-Ampt model is very simple and the model parameters can be directly obtained from the physical and hydraulic properties of soil [18]. The Green-Ampt equations for cumulative infiltration F(t), and infiltration rate *f* with time are [14]:

$$F(t) = Kt + \psi \Delta \theta \ln\left(1 + \frac{F(t)}{\psi + \Delta \theta}\right)$$

$$f = K\left(1 + \psi \frac{\Delta \theta}{F}\right)$$

Where;
F(t): The cumulative infiltration, (cm)
F: The infiltration rate, (cm/hr),
K: Hydraulic conductivity, (cm/hr),
ψ: Wetting front capillary pressure head, (cm),
$\Delta\theta$: Change in moisture content, which is a difference between porosity η, and initial soil water content, θ_i, and finally
T: Time, (hr).

4.1 Modeling the Existing Infiltration Regime for IB1

The purpose of this step was to search for the best model that fit the real situation in the infiltration basins in terms of infiltration rate and cumulative infiltration. Fining the best fit model will help us determine the dominating soil layer that control the infiltration process. Several trials were performed using different hydraulic conductivities and different soil properties to calculate the cumulative infiltration and the infiltration rate for the existing infiltration regime to simulate the real infiltration rate, see Figure 8. Figure 9 is representing the real cumulative infiltration and infiltration rate for the same basin from the same model.

It was found that the best model to fit the existing situation for infiltration can be achieved when K (0.833-0.98 cm/hr) as shown in Figure 10. With this value of K and other associated soil properties the resulted Greet-Ampt model was found to match the data recorded by Palestinian Water Authority (PWA) for the year 2013 with very high correlation coefficient ($R^2 = 0.995$).
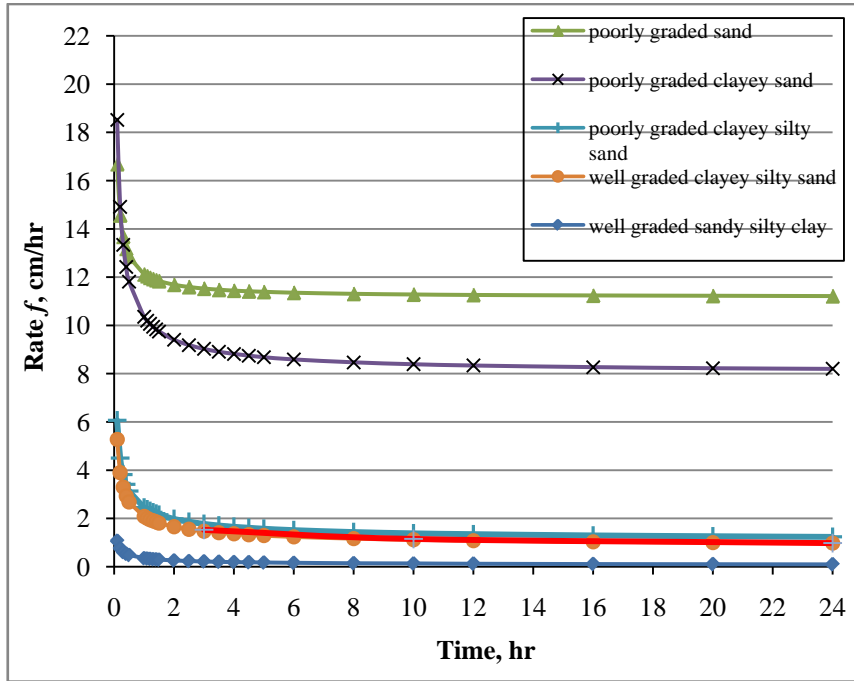
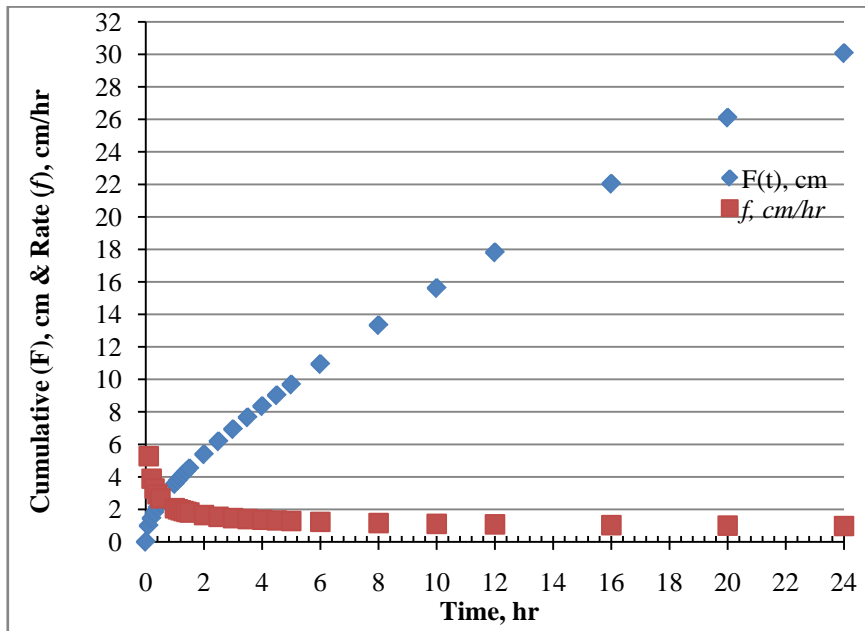Figure 8: Infiltration Rate with Time, for Different Soil Parameters
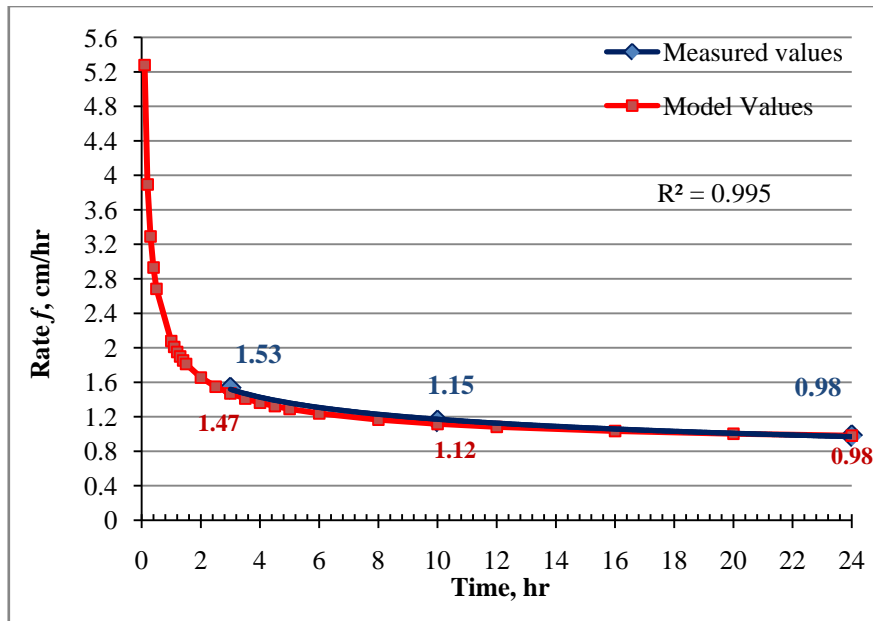

Figure 9:The Best Fit Model for Real Infiltration

Figure 10: Measured and Model Values for Infiltration Rate at IB1

4.2 Enhancement the Upper Layer Infiltration Rate for IB1

The geological cross section for the soil shows a clayey sand layer, which is a poorly graded clayey sand, slightly light brown with little gravel (Kurkar) exist at variable depths. The layer is of low to medium plasticity, and contains (3.0-10.0)% gravel, (60-85)% sand, and (15-40)% fines, and with lowpermeability.

The clayey sand layer is spreading widely at the first two meters in the basin. The effect of the clayey sand layer on the infiltration rate was obvious during modeling the existing infiltration regime. In order to enhance the infiltration rate; this layer should be completely removed and should be replaced by a new sand layer with high permeability. Sand can give permeability of 11.78cm/hr (2.827m/d) [15]. A model describing the infiltration for the proposed sand layer was performed. The output of the model is shown in Figure 11.

The output of the model illustrating that the infiltration rate can reach 11.86cm/hr (2.85m/d) after 24 hours with cumulative infiltration of 293.2cm if the top soil of the basin is replaced by the proposed sand layer.
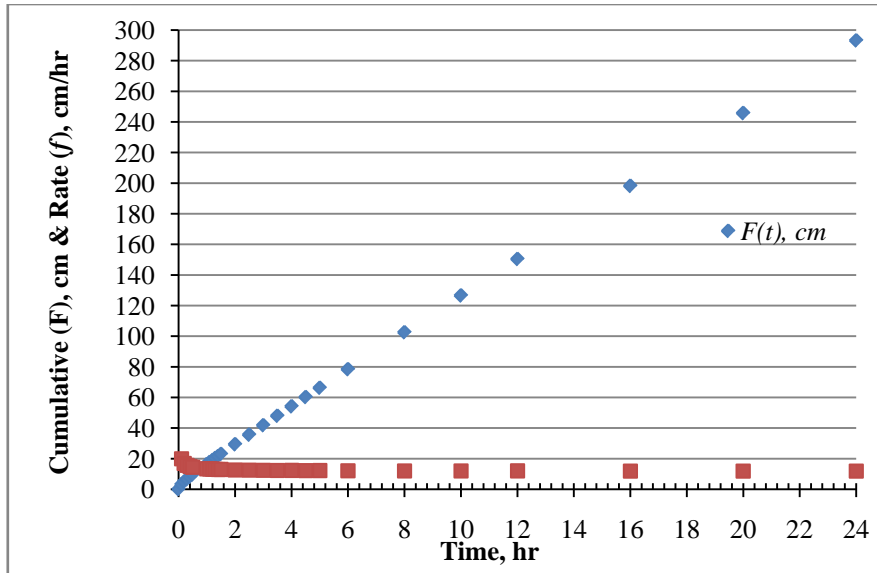
Figure 11: Cumulative Infiltration, & Rate with Time for the Proposed Layer

4.3 Enhancement the Lower Layers Infiltration Rate for IB1

According to the geological cross section for the soil; a layer of sandy silt clay exists at depth ranged from 6.40m to a depth of 7.50m (0.90m thick) in the middle of IB1, as this layer appeared only on BH3. This layer is dark brown with little gravel (Kurkar), and the layer is of medium plasticity, and of low permeability as discussed previously. The effect of this layer was clear on the infiltration rate during modeling the infiltration because this layer has a very low vertical hydraulic conductivity (0.042cm/hr). Another soil layer was found at depth ranged from 8.0 m to a depth of 9.0m (1.0m thick) at BH2, and BH5, this layer is same as the first two meters of the basin.In order to enhance the infiltration rate, injection piles was suggested to penetrate the deep low permeability layer. Sichardt equation was used to estimate the diameter, depth, and the gravel filter media. The relationship between the velocity and hydraulic conductivity of the aquifer is expressed by Sichardt equation [19].

$$V_a < \frac{\sqrt{K}}{15},$$

Where;
V_a is the approach velocity in m/s, and K is the hydraulic conductivity of the aquifer in m/s. Safety factor of 2 is usually used for safe design considerations.Based on that, 60 piles with 0.60m diameter and 14 meters in length filled with fine gravel media with high permeability (450m/d) [15] should be distributed in an area of90x50m^2 from the middle of IB1 as shown in Figures 12. These piles should be installed below the upper 2.0-meters sand layer mentioned earlier and should continue at least 5 meters below the low permeability layer
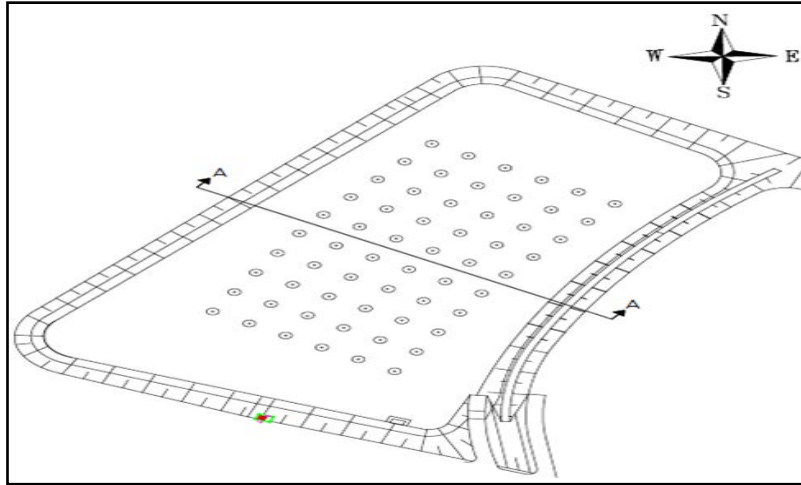
Figure 12: Distribution of Piles at IB1

An Un-plasticized Poly Vinyl Chloride (UPVC) pipe of 0.60m diameter was suggested for the injection piles. This pipe will be solid from the top up to 9 meter depth to prevent clogging of the gravel filter media from the entrance of the fine particles from the surrounding soil (clayey sand at depth 8-9m, and sandy silty clay at depth 6.5-7.40m) and will be perforated for at least 5 meters below the 9.0 meter depth to maintain high specific area for the dispersion of the infiltrated water (Figure 13).

4.4 Enhancement the Wetting and Drying Cycles

Longer drying time tends to be more effective in re-establishing infiltration rates compared with shorter drying time. It is reasonable to expect that a more thorough surface drying with corresponding cracking and breaking up of the surface clogging layer would increase infiltration rate [20].For primary effluent the ratios of loading to drying periods within a single cycle are generally less than 0.2 to allow for adequate drying, but in all cases, to avoid excessive soil clogging, the hydraulic loading period for primary effluent does not exceed 1-2 days regardless of season or treatment goals [21].

For treatment goals with primary effluent are to maximize infiltration rates, it was found that performing 35 cycles of wetting and drying during the year with 2 days of wetting in summer and winter and 7 days of drying in summer and 12 days of drying in winter, will help to reach the optimal infiltration rate. Also, soil plowing should be performed immediately after each drying cycle for the basins will maintain good infiltration rate and to prevent accumulation of the OM in the top soil layer.
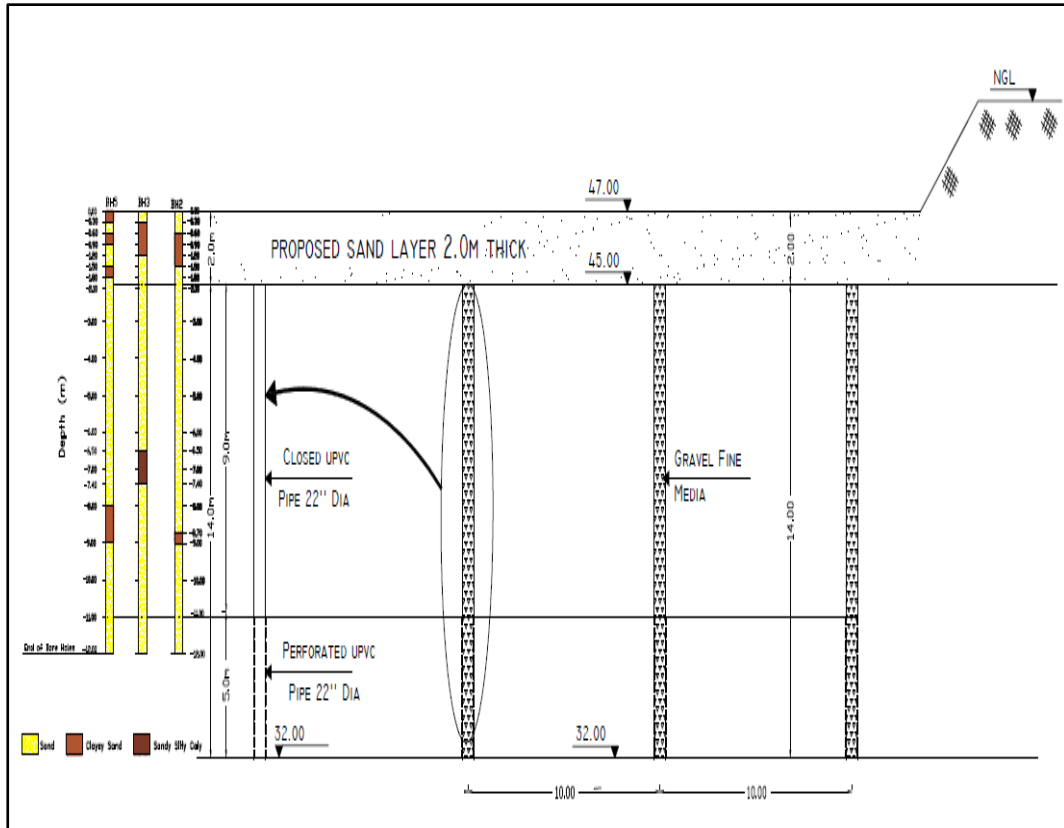
Figure 13: Cross -Section A-A

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