Derivation of New Design Equations for Subsurface Drainage to Lower the Water Table in a Soil Layer Over-topping an Aquifer

Amgad S. Elansary[1], Ashraf M. Ghanem[2], Gamal H. Elsaeed [3], and Neveen B. Abdelmageed[4]

1. Abstract:

There is an essential need to construct hydraulic structures along any waterway such as weirs, regulators….etc. Regulators are very important parts in the modern irrigation system, but they have some side effects as any other intervention. One of its negative impacts is the rise of the groundwater levels in its surroundings. This increase in water levels, both locally near the new barrage and upstream, will result in changes in groundwater levels in the aquifer system both upstream and downstream of the barrages. A drainage system must be developed to minimize the effect of this problem that is applicable for the Nile valley geology (clay or silt clay overlaying coarse sand).

This study develops design equations, which incorporate the effect of thickness of the top layer and soil parameters on perforated pipes, discharge and spacing between the pipes. These equations are derived for a special case, which consists of two layers, the upper layer being a semi pervious layer of clay or silty clay and the lower aquifer being as coarse sand. A computational model (Micro FEM) has been used to simulate a hypothetical aquifer system for different scenarios.

Keywords:
Subsurface Drainage; Underground Water; Groundwater Lowering; River Nile Valley .

المقدمه:
دعت الحاجه لانشاء العديد من المنشآت الهيدروليكيه على طول المجارى المائيه مثل الهدارات و القناطر . و تعد القناطر من اهم المنشآت المستخدمه و لكن لها من المساوئ مثل باقى المعترضات المائيه مثل إرتفاع منسوب المياه بالمجرى المائى مما يؤدى الى زيادة منسوب المياه الجوفيه بجانب و أمام المنشأ و لهذا يجب وضع نظام لتقليل هذه المشكله و خاصه فى منطقة وادى النيل لما لها من تكوين جيولوجى خاص و هو طبقه شبه منفذه تعلو طبقه من الرمل.
فى هذا البحث تم إستنتاج معادلات تختص بتأثير سمك و خواص التربه للطبقه العلويه على كميه المياه المتجمعه من مواسير الصرف المثقبه و تأثيرها أيضا على المسافه بين المواسير. و قد أستخدم فى هذا البحث نموذج للمياه الجوفيه لتمثيل السريان فى الطبقات تحت السطحيه.

2. Introduction:

The increase of groundwater level results in some adverse effects. Papadopoulos et al. (2005) studied the effects on structures and constriction activities. Drablos and Melvin (1991) investigated the effects of high groundwater levels on plants. They concluded that the drainage is an important and profitable practice for conservation of farming. Through drainage, it is possible to improve crop production and to use more intensive farming practices on flat lands. The removal of excess water from the saturated soil mass by drainage or dewatering. Several studies have discussed the hydro-geological aspects of the following dewatering methods: ditches and

[1] Professor of Hydraulics, Faculty of Engineering, Cairo University .
[2] Assoc. Professor, Faculty of Engineering, Cairo University .
[3] Assoc. Professor, Faculty of Engineering, Shobra, Banha University .
[4] Ph.D. Candidate, Faculty of Engineering, Shobra, Banha University .

sumps (Donald et al. 1983), well point systems (Charles and Stephen 2002), pumping well system (Tokgoz et al. 2002), cut off dam (Donald et al. 1983), and subsurface drainage (Drablos and Melvin 1991, and Skehan and Christen 2001).

The Nile Valley aquifer system is composed of Late Pleistocene graded sand and gravel capped with a Holocene silty clay layer. In the central portion of the Nile Valley, the Holocene layer acts as a semi-confining layer to the underlying Pleistocene aquifer. The thickness of the upper layer varies in the central portion and in some places it reaches 20m thick. In the outer fringes, the silty clay layer disappears and the aquifer becomes unconfined, see Figure (1). The intervention of the upper layer and the lower one is affected by the lowering of the groundwater level and the optimal design of the dewatering system.

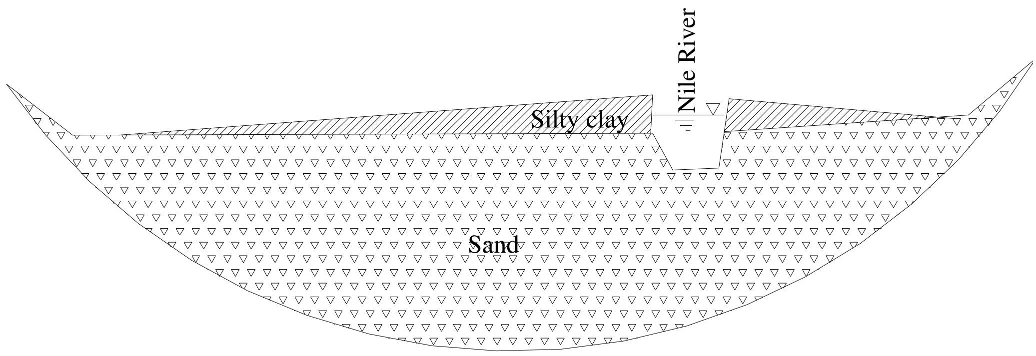

Figure 1: Cross Section in the Nile Valley

The Current Equation

Hooghoudt (1964), studied the spacing of tile drains and developed the following equation:

$$q = \frac{4K_a \cdot h^2}{L^2} + \frac{8K_b \cdot d_e \cdot h}{L^2} \tag{1}$$

Where: q is the flux discharge (m/day), L is the drain spacing (m), h is the initial head (m), K_a is the Hyd. conductivity (H.C.) of the layer above the drain level (m/d), K_b is the H.C. of the layer below the drain level (m/d), and d_e is the equivalent depth to the impermeable layer (m)

For *D/L*<0.31: $d_e = \dfrac{D}{1 + \dfrac{D}{L}\left(2.55 \log_e \dfrac{D}{r} - 3.5\right)}$

For *D/L*>0.31: $d_e = \dfrac{D}{2.55\left(\log_e \dfrac{L}{r} - 1.15\right)}$

Where: D is the depth to the impermeable layer from the drain centerline (m), and r is the radius of collectors (m)

Ernst equation (Ritzema 1994), can be used to calculate the drainage flux:

$$q_{drain} = \frac{\Phi_{gwl} - \Phi_{drain}}{\gamma_{drain}} \tag{2}$$

Where: q_{drain} is the drainage flux, (Φ_{gwl} and Φ_{drain}) are the elevation of the water table mid-drain spacing and in the drain, and γ_{drain} is the drain resistance.

$$\gamma_{drain} = \frac{L^2}{8K_{hprof}d_{eq} + 4K_{hprof}(\Phi_{gwl} - \Phi_{drain})} + \gamma_{entr} \qquad (3)$$

Where: K_{hprof} is the horizontal saturated hydraulic conductivity above the drainage base, and γ_{entr} is entrance resistance.

The drainage equations of Hooghoudt and Ernst are both steady state equations but differ in the way water flow through the saturated zone between the water table and the drains. Whereas in Hooghoudt's equation only horizontal flow is assumed from mid-drain spacing to the drainage laterals, in Ernst equation the streamline of water is subdivided into three separate sections (vertical, horizontal, and radial flow). The sum of the head loss over each section is equal to the total available head. With Hooghoudt's equation only the water flow to the drains is in a homogeneous profile with the drains above or on the top of an impervious layer or a two layered profile with the drains at the interface of the two layers. On the other hand, with Ernst's equation water flows to the drains in a two layered profile where the drains are located on either the top or the bottom layer can be analyzed.

Toksöz and Kirkham (1971) introduced a set of 16 figures; containing 29 graphs for easy calculation of the drain spacing in two-layered soils. Drain spacing calculated using Dagan's equation for the two-layered soils concur with the spacing calculated from the graphs.

Bazaraa, et al., (1986) studied the artesian and anisotropic effects on drain spacing. Subsurface drainage systems installed in the soil overlying artesian aquifers should be spaced to handle both upward artesian water flow and normal downward seepage flow from irrigation and rainfall. Proper drain spacing depends on several parameters, while a narrower than normal spacing is required for drains subject to artesian conditions. The hydraulic conductivity of the soil above an artesian aquifer determines the contentious of water flowing to the drains and the magnitude of the upward artesian water flux for a given piezometric head and soil layer thickness. Since water movement to subsurface drains depends on both the horizontal and vertical components of hydraulic conductivity, anisotropy of the soil affects the drain spacing. For most soil formations, the hydraulic conductivity in the horizontal direction exceeds that in the vertical direction. Neglecting anistropy may lead to under-design of the drainage system for a formation above an impermeable layer and can lead to over-design of a drain system for a formation subject to artesian conditions with no downward flow. For a soil subject to upward flow as well as downward flow, anisotropy effects depend on the magnitude of the different parameters influencing the problem.

The main contribution in this study is to provide a straight forward methodology to determine the best position for perforated pipes and its discharge. The deducted model is applicable for every soil of same geological composition.

3. Hydrogeology of Nile Valley:

3.1. Geomorphology:

Abd El-ghaffar (1997), the geomorphology of the Nile Valley is dominated by three distinct units:

1. The central part of the Nile Valley comprises a young alluvial plain. The gradient of the ground surface is generally very low with an elevation 72 to 64m asl from the east to west.
2. The central area is confined to the north and south by an older alluvial plain. The transition to this second unit, along the edges of the valley, is characterized by a significant increase in ground elevations, the older unit is 10 to 25m higher.
3. The Nile Valley is bounded by a structure plateau. The border between this third unit and the alluvial plain is marked by an abrupt rise in the ground surface to elevations in excess of 400m asl.

3.2. Geology:

Abd El-Aziz (1984) stressed that the groundwater model must accurately reflect the observed geologic structure of the region. Therefore, all available information from existing reports were utilized. The local stratigraphical succession in the Nile Valley can be characterized (from the ground surface down) as:

- The Holocene (Neonile and young wadi deposits) unit representing the central portion of the Nile valley (young alluvial floodplain) and young wadi deposits located on the outer regions (old alluvial floodplain). The unit consists of silty clay interacted with gravel and sand, and varies in thickness from 0 to 20m. In addition to being the upper aquifer, the surface of this unit is the fertile agricultural land of the Nile valley.
- The sand and gravel of the late Pleistocene (pre Nile deposits) which form the lower aquifer in the Naga Hammadi area. The thickness of the unit varies from 40 to 230m. This aquifer is of high importance for drinking water supply by pumping, giving high yields. The lower aquifer is under several geological units which are interpreted as aquicludes (barriers) for the overlying aquifers, or secondary aquifer systems. These are of little importance as sources of water supply because of low yields and the relatively high salinity of the groundwater. Their sequence is as follows:
    1. Sediments of the Pilo-Pleistocene unit (proto-Nile/ pre-Nile deposits) form an aquifer of secondary importance. This unit comprises clay, sand and gravel which are locally capped by travertine beds. The Pliocene clay is considered to be the base of this aquifer.
    2. The Eocene limestone consists of bedded limestone and chalk and acts as another aquifer which is not exploited.
    3. The Paleocene late cretaceous unit is the lowest aquiclude above the Nubian aquifer.

3.3. Aquifer Geometry:

Summarizing the geological conditions in the Nile Valley, aquifer system is composed of Late Pleistocene graded sand and gravel capped with a Holocene silty clay layer. In the model, the Holocene silty clay cap and the Late Pleistocene sand and gravel are defined as separate aquifer systems which are hydraulically interconnected. In the central portion of the Nile valley, the Holocene layer acts as a semi confining layer to the underlying Pleistocene aquifer. The thickness of the upper layer varies in the central portion and in some places is up to some 20m thick (RIGW (1994)). In the outer fringes, the silty clay layer disappears and the aquifer becomes unconfined, as shown in Figure (1).

The aquifers underlying the Nile Valley have been simulated as two aquifers. The upper aquifer is represented by the silty-clay cap, while the lower aquifer is represented by the sand aquifer. Interchange between the two aquifers has been simulated through the specification of a leaky layer, having a vertical H.C. of one-tenth the horizontal H.C. for the upper layer.

3.4. Hydraulic Conductivity (L/T) (H.C.):

The definition of H.C. throughout the study area is important as it is one of the most critical parameters in determining groundwater flow in the aquifer systems. H.C. values were determined during earlier hydro-geological studies in the Nile Valley by RIGW (1994). The H.C. of the upper layer varies from 0.01m/d to 2.0m/d. The lower layer is formed of gravel and coarse sand with a maximum depth of about 300m and average coefficient of H.C. greater than 50m/day.

4. Computer Models of Groundwater:

The approach adopted for simulation of groundwater conditions is a quasi three-dimensional approach, which simulates horizontal flow in each aquifer as two dimensional flow in addition to vertical flow between the aquifers. To achieve this, a multi layer finite element model has been utilized for the study area. The computational model selected for this study is MicroFEM version 3.6, developed by C. Hemker and R. de Boer (1997). MicroFEM has been developed to create, and analyze multiple aquifer steady state and transient groundwater flow models, with a maximum of 20 aquifers and 50000 nodes per aquifer. Confined, leaky, phreatic and anisotropic aquifers can be modeled. For presentation purposes, results in graphical form can be copied to the clipboard or exported as DXF or HPGL files and edited / printed using appropriate Windows™ software. Further options include interactive grid adaptations, water budgets, profiles and cross sections.

5. Development of Different Scenarios:

In order to be able to develop empirical relations which can describe the above relationships, large amounts of data are required for different cases for aquifer thickness, groundwater depth, pipe spacing…etc. These parameters are as shown in Figure (2): the soil H.C. of the lower layer (k_l); the initial head above pipe centerline (ho); the spacing between pipes (L); the final head above pipes which is measured at mid point between the two pipes (h); the discharge entering the pipe (Q); the thickness of upper layer (th); and H.C. of upper layer (k). For this purpose, the computational model MicroFEM (Hemker & Njisten, 1996; Diodato, 2000) was utilized. Hypothetical scenarios were developed which cover a broad range of possible field conditions. Five different values for the upper layer H.C. (0.01, 0.1, 0.2, 0.5, and 1.0m/day) and five values for the upper layer thickness (2.0, 3.0, 5.0, 9.0, and 12.0m) were used. Four different values for lower layer H.C. (50, 60, 70, and 100m/day) were studied to determine the effect of the lower layer H.C. A system of perforated pipes placed at four different values of spacing (10, 20, 50, and 100 m) was introduced to the model. Twenty five groups of runs were made for each group, while the H.C. and the thickness of upper layer were kept constant; the water head above the pipes, and the spacing between the pipes were the variables. This gives a total of 25 x 6 = 150 runs. These runs provided the basis for the derivation of the empirical relations. The discharge entering the perforated pipes was determined after each run by water balance of the model.

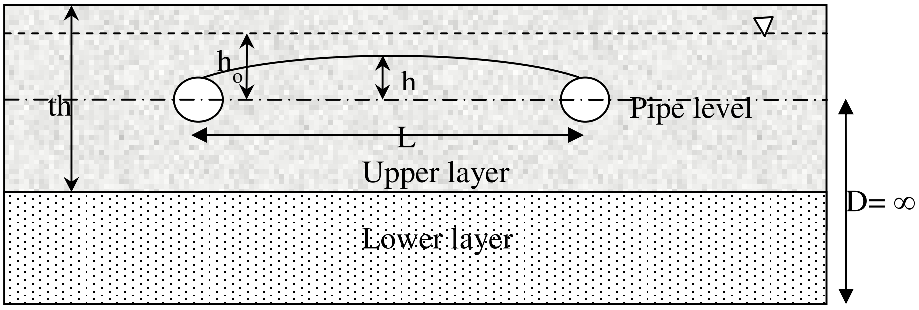

Figure 2: Sketch showing the different parameters used

6. The Model Construction:

The hypothetical case study area is 0.4 km^2. It extends 2.0 km from the east to the west, and extends 0.2 km from the north to the south. The model domain was divided into 1332 elements and 752 nodes. The average nodal area is about 0.008 km^2, as shown in Figure (3).

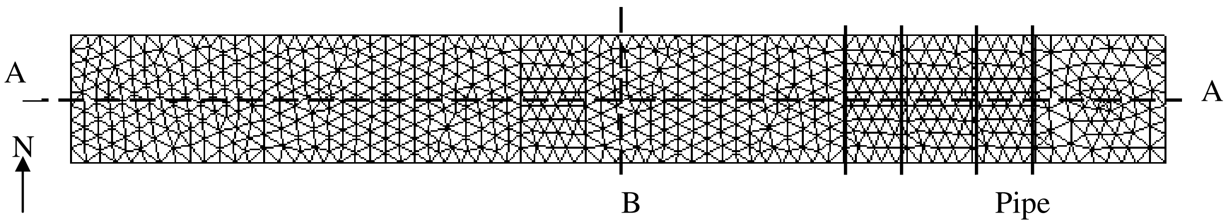

Figure 3: Finite Element Mesh for the numerical model

7. Boundary Conditions for the Hypothetical Case:

The area is surrounded by two different hydraulic conditions, fixed head of 35.5m along the North boundary, fixed head of 35.0m along the South boundary and no flow along both the eastern and western boundaries. Thickness of the top layer and its H.C. were variables. Figures (4) and (5) show the water table profile at section (A-A), and (B-B) respectively in case of soil H.C. 1m/day and the upper layer thickness is 2.0m without using any dewatering system.

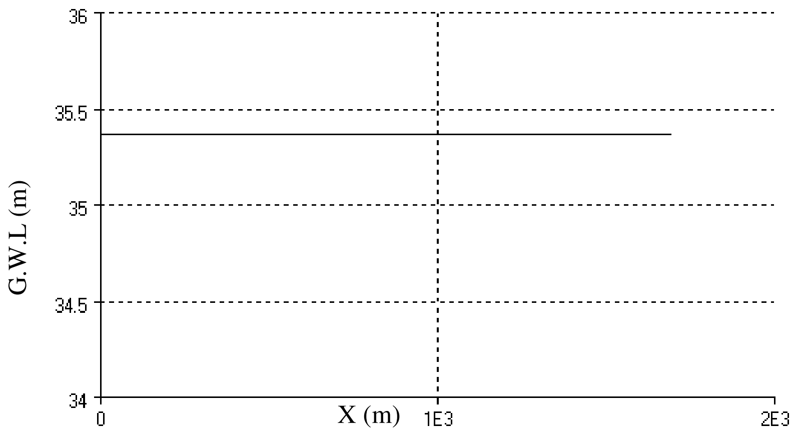

Figure 4: Water table profile at section (A-A) without perforated pipes

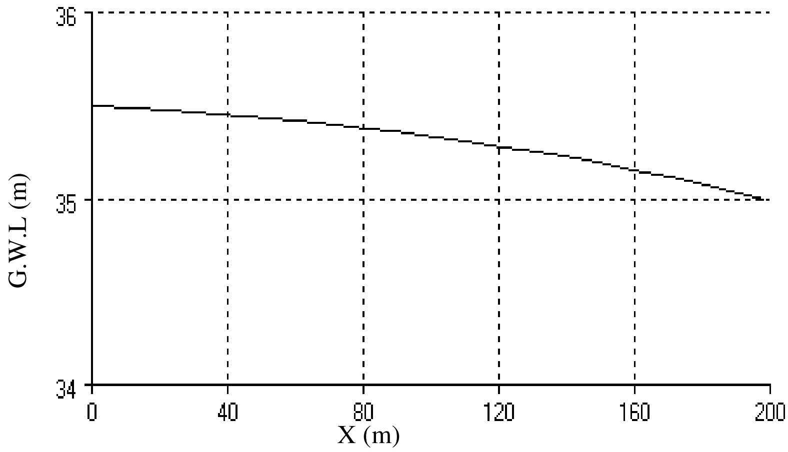

Figure 5: Water table profile at section (B-B) without perforated pipes

8. Dewatering System:

The area was dewatered by placing a system of perforated pipes with variable spacing at fixed head of 34.0m. The perforated pipes were divided into 5 sections. For each section the average of the initial head, the final head, and the discharge entering this section were computed. Figure (6) shows the water table profile at section (A-A) after placing the pipes in case of soil H.C. of 1m/day, upper layer thickness is 2.0m and the pipe spacing is 100m. All the results were used in "Minitab Program release 12 for Microsoft Windows" and "Datafit version 8.0.32 developed by Oakdale Engineering (1995-2002)" to derive the equations.

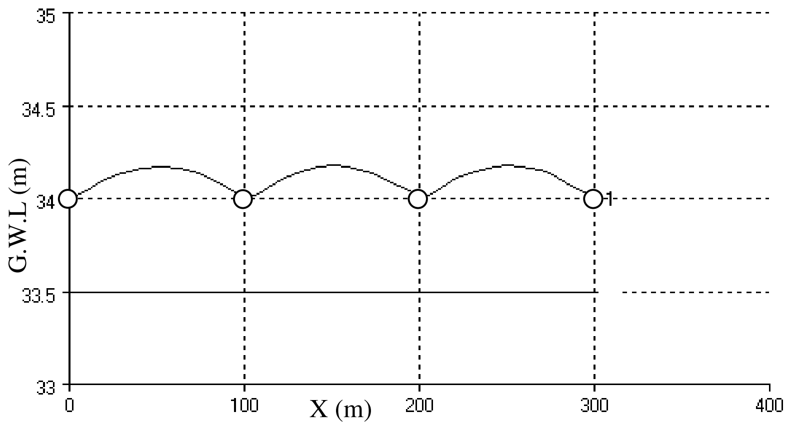

Figure 6: Water table profile at section (A-A) with perforated pipes

9. The Effect of the Upper Layer Thickness:

The thickness of the upper layer affects the pipe spacing and the pipe discharge. Figure (7) shows the effect of the upper layer thickness on the pipe spacing. It reveals that an increase in the thickness of upper layer by 100% will cause a decrease in the spacing between the pipes by 2%. Figure (8) shows the relation between the thicknesses of the upper layer on the discharge of the pipe. It reveals that an increase in the thickness of the upper layer by 100% will cause decrease in the pipe discharge by 2%. From the above it can be deducted that the upper layer thickness has a little effect on the drainage system.

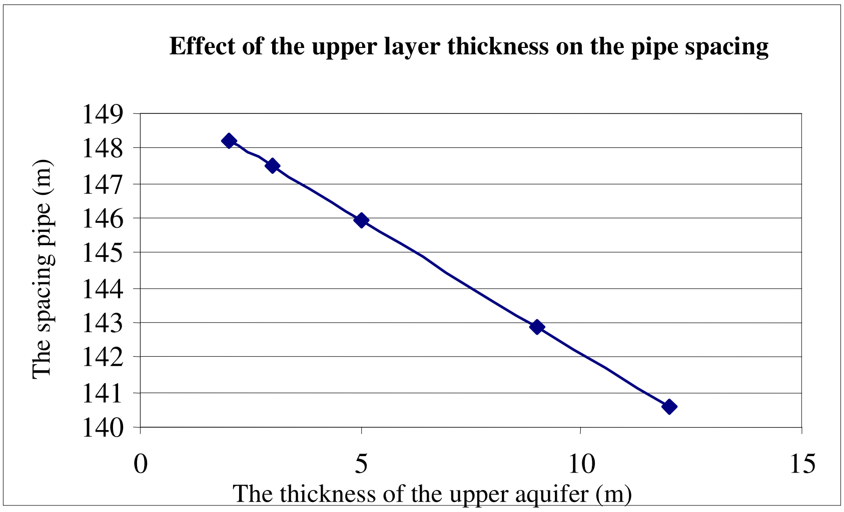

Figure 7: The effect of the upper layer thickness on the pipe spacing

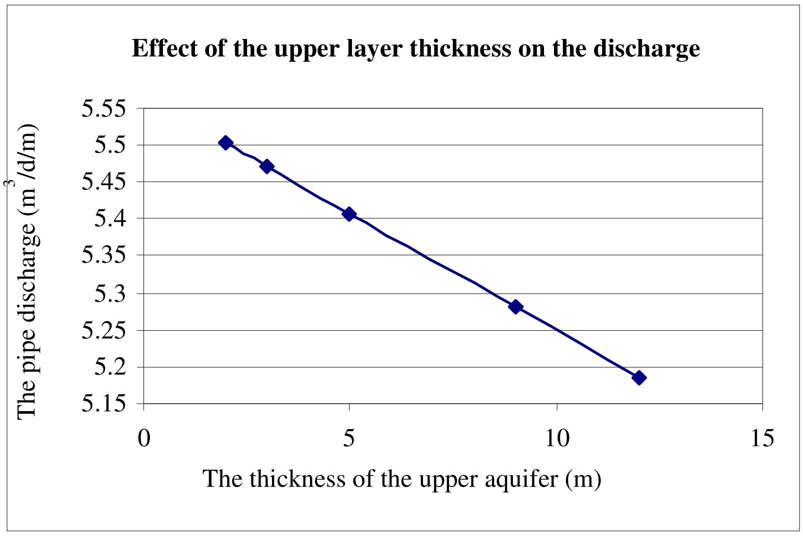

Figure 8: The effect of the upper layer thickness on the pipe discharge

10. The Effect of the Upper Layer H.C.:

The soil H.C. affects the pipe spacing and the pipe discharge. Different values for the soil H.C. were studied during this study. Four values for the soil H.C., 0.01, 0.2, 0.5, and 2.0m/day were considered. Figure (9) shows the effect of the soil H.C. on the spacing. It reveals that an increase in the soil H.C. for the upper layer by 100% will cause an increase in the pipe spacing by 25%. Figure (10) shows the relation between the soil H.C. for the upper layer on the discharge of the pipe. It reveals that an increase in the soil H.C. for the upper layer by 50% will cause an increase in the pipe discharge by 60%.

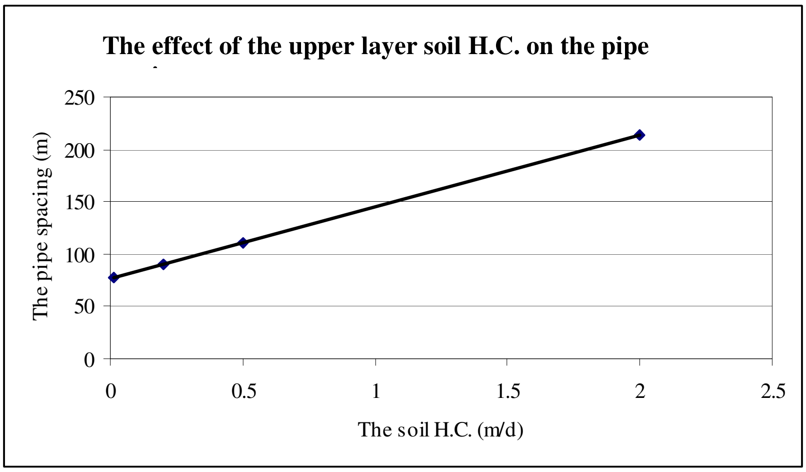

Figure 9: The effect of the upper layer soil H.C. on the pipe spacing

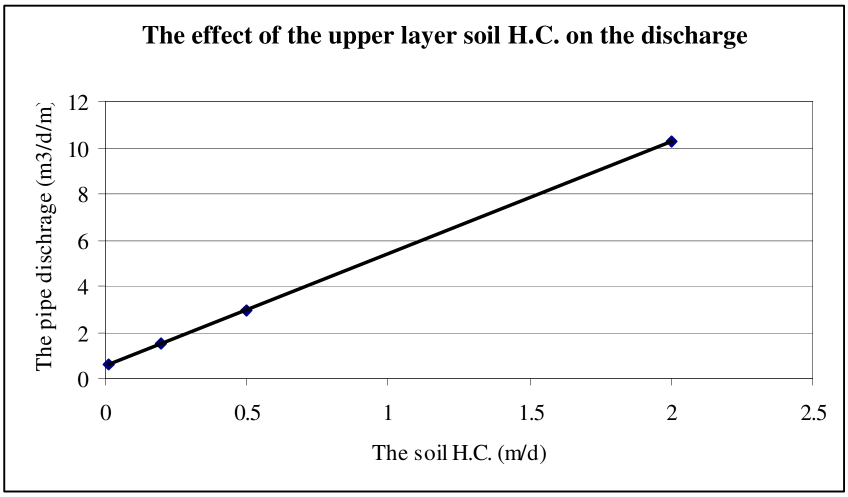

Figure 10: The effect of the upper layer soil H.C. on the pipe discharge

11. The Effect of the Initial Head:

The initial head has an effect on the pipe spacing and the pipe discharge to solve the elevated groundwater table problem. Different values for the initial head were investigated using the model. Figure (11) shows the effect of the initial head on the pipe spacing. It reveals that an increase in the initial head by 100% will cause a decrease in the pipe spacing by 25%. Figure (12) shows the relation between the initial head and the discharge of the pipe. It is clear that an increase in the initial head by 100% will cause an increase in the pipe discharge by 4%.

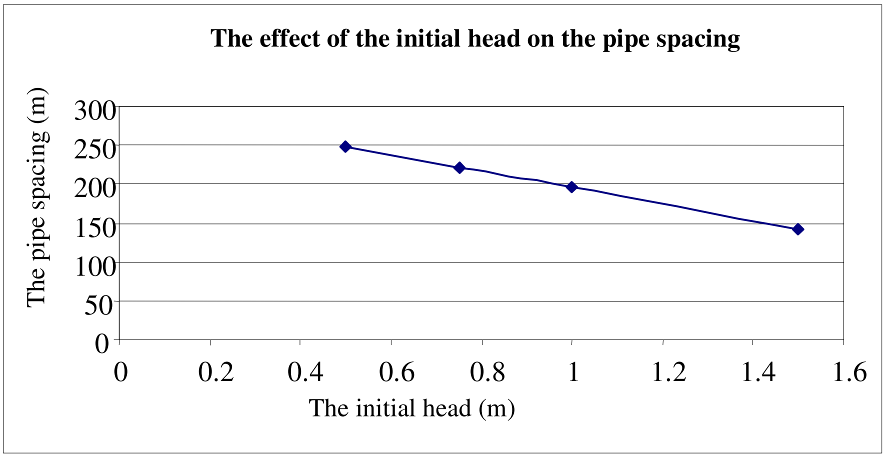

Figure 11: The effect of the initial head on the pipe spacing

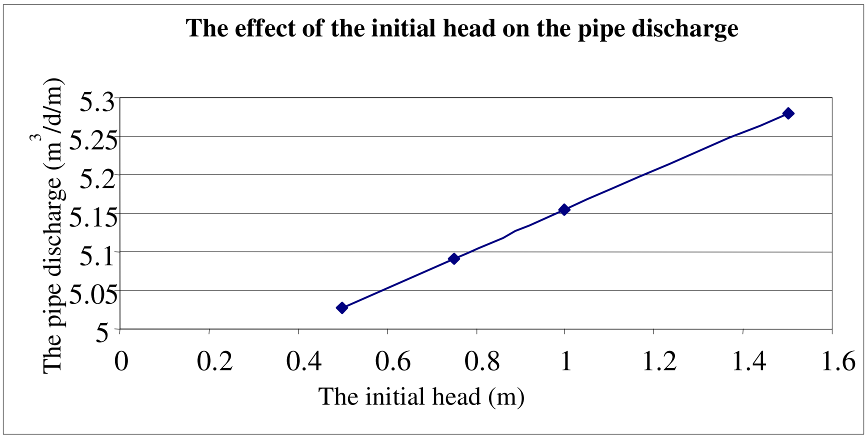

Figure 12: The effect of the initial head on the pipe spacing

12. Effect of the Lower Layer H.C.:

Different values for the soil H.C. were studied during this study. Four values for the soil H.C., 50, 60, 70, and 100m/day were considered. Figure (13) shows the relation between the soil H.C. of lower layer on the discharge of the pipe. It reveals that an increase in the soil H.C. for the lower layer has no effect on the pipe discharge.

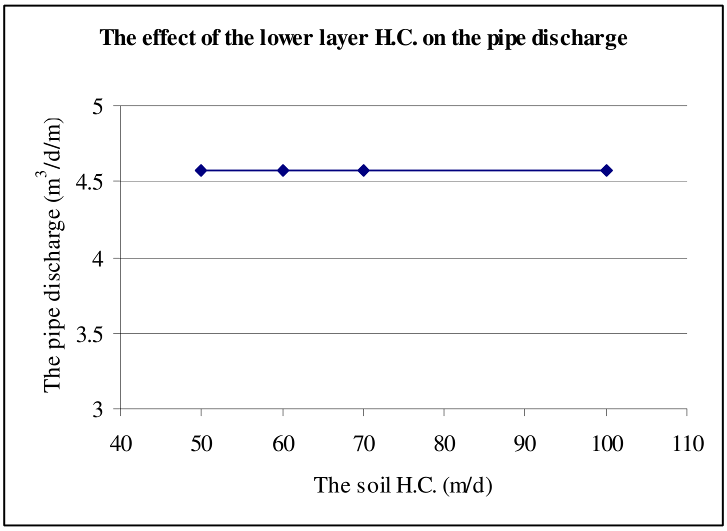

Figure 13: The effect of the lower layer soil H.C. on the pipe discharge

13. The Relationship Between the Different Variables:

Two procedures were used for the derivation of the mathematical relationships between the different variables, the first using the regression analysis tool of "Minitab" while the second employs the program "Datafit". The relation between the pipe spacing (L), the upper layer thickness (th), the H.C. of the upper layer (k), the initial head (ho), and the final head above pipe (h) can be expressed as follows:

$$h = 0.00273 \times th - 0.244 \times k + 0.00348 \times L + 0.371 \times h_o - 0.3347 \quad (4)$$

$$L = -0.768 \times th + 70.61 \times k + 283.45 \times h - 105.72 \times h_o + 96.02 \quad (5)$$

$$q = 0.003 \times k + 6.8E\text{-}07 \times L\text{-}1.93E\text{-}05 \times th + 1.54E\text{-}04 \times h_o + 2.86E\text{-}05 \quad (6)$$

With:

Coefficient of Multiple Determination (R^2) = 0.93

Where: "h" is the final head above pipes which is measured at the mid point between the two pipes (m), "th" is the thickness of the upper layer (m), "k" is the soil H.C. of the upper layer (m/day), "L" is the spacing between pipes (m), "h_o" is the initial head above the pipe centerline (m), and q is the flux discharge (m^2/day)/m

The result of the equation fit by "Datafit" is:

$$h = \exp(0.0062 * th - 0.552 * k + 0.01 * L + 1.133 * h_o - 3.236) \quad (7)$$

$$q = 3.1 * k + 0.001 * L - 0.018 * th + 0.161 * ho \quad (8)$$

With:

Coefficient of Multiple Determination (R^2) = 0.993

In this equation the unit flux discharge is mm/d

14. Comparison Between Hooghoudt's and the New Equations:

The new developed equations were compared with Hooghoudt's equation, and Ernst's equation. Two cases were evaluated. The first case is for large upper layer thickness, the initial head varies from 0.5, 0.75, and 1.0m, the spacing between pipes varies from 50, 100, and 120m, and the soil H.C. of the upper layer varies from 0.01, 0.05, and 0.1m/d. Figure (14) presents the comparison for an upper layer thickness of th = 9.0m (Thick layer).

The Figure reveals that the equations gave almost the same discharge flux for different cases.

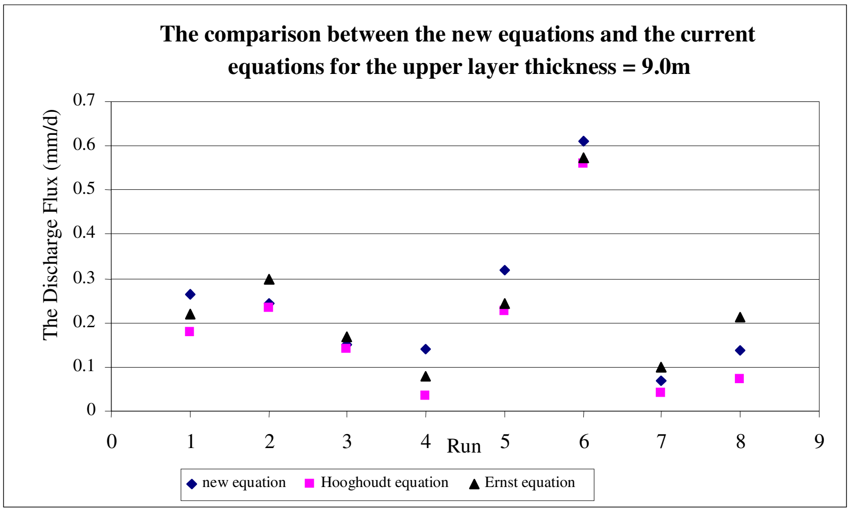

Figure (14): The comparison between the new equations and the current equations for an upper layer thickness of 9.0m

The second one is for a thinner upper layer thickness. Figure (15) presents the comparison for a thinner upper layer thickness of th = 2.0m. In the current equations the pipe spacing depends on the discharge rate but in the new derived equation the pipe spacing depends on the final head and thickness of the upper layer.

The scheme of groundwater flow into the perforated pipe is affected by soil geology. The soil under investigation is composed of two distinct layers. Flow discharge is a function of some geological parameters including upper layer H.C., initial and final heads, and the thickness of the upper layer. The first three parameters are introduced in the current equations. The current study introduces the effect of upper layer thickness on the flow discharge. Comparing the new model including the upper layer thickness parameter with those of Hooghoudt and Ernest gives close results for the thick upper layer case. On the other hand this comparison is not as close for the thin upper layer thickness case as shown in figure (14).

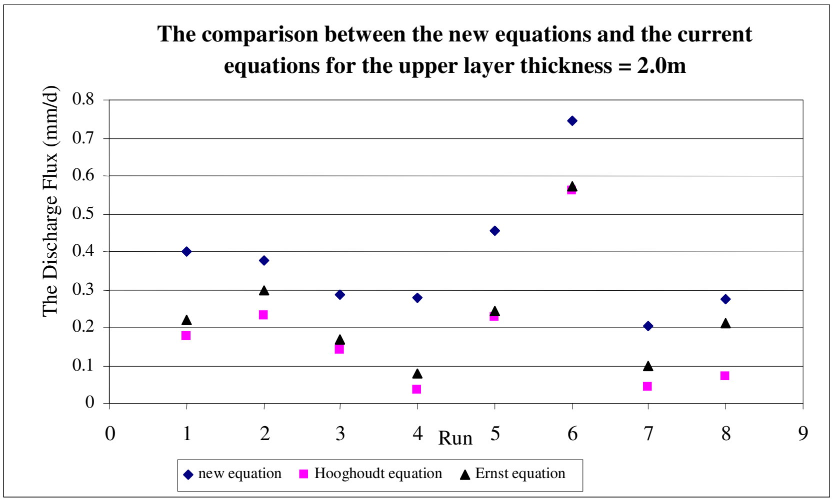

Figure (15): The comparison between the new equations and the current equations for the upper layer thickness of 2.0m

15. Application of the Equations on a Case Study

Elrizqa village is located 1.5km from the New Naga Hammadi Barrage (NNHB). It suffers from the construction of NNHB. The sewer system, perforated pipe network are the effective alternative groundwater lowering system inside the urban area. The drains network is placed at about 1.7m below the ground level. The above equations will be used to calculate the discharge of the perforated pipe and lowering the groundwater. The intent is to compare between the pipe spacing that already placed and the maximum pipe spacing that can be placed which results in a sufficient groundwater lowering as calculated from the derived equations.

The case study area has an upper layer H.C. of 0.17m/d, with thickness of 9.0m. The pipe spacing varies from 40m to 100m and the initial head varies from 0.6 to 1.2m. The maximum pipe spacing of the final head at 0.5m above the pipe level can be obtained from equation (5) as follows:

$$L = -0.768 \times th + 70.61 \times k + 283.45 \times h - 105.72 \times h_o + 96.02$$

$$L_{max} = -0.768 * 9 + 70.61 * 0.17 + 283.45 * 0.5 - 105.72 * 0.7 + 96.02 = 168.83m$$

Table (1) shows the comparison between the existing pipe spacing and the maximum pipe spacing that was obtained from the derived equation . The decreasing ratio between the maximum pipe spacing obtained from the new equation and the actual pipe spacing is about 60%.

Table (1) The data of pipe network at Bakhaness

Initial head (m)	Actual pipe spacing (m)	Maximum pipe spacing (m)	Decreasing ratio (%)
0.8	90	158.2613	43
0.8	60	158.2613	62
0.7	100	168.8326	40
0.5	60	189.9753	68
0.6	38	179.4039	78
0.9	37	147.6899	74
0.5	70	189.9753	62
0.4	68	200.5466	66

Figure (16) shows the comparison between the final head obtained from the model and the final head obtained from the derived equation at different locations. The figure reveals that the equation gives nearly the same final depth of water for different cases.

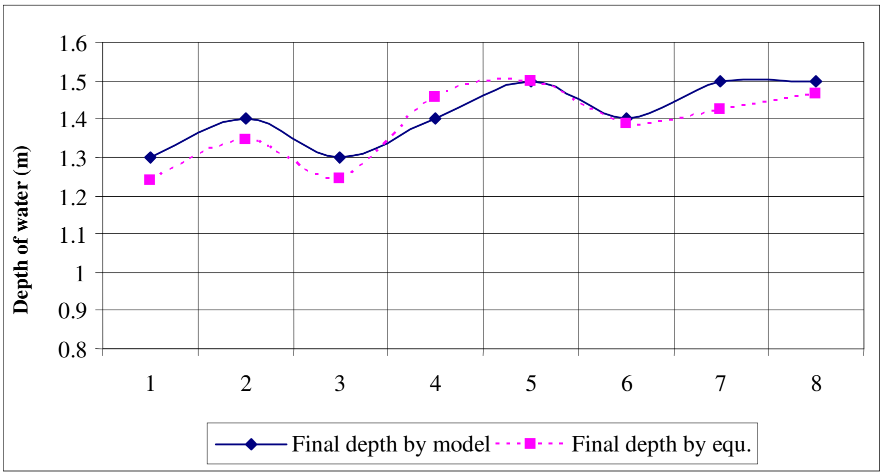

Figure (16): The comparison between the final depth of water in model and the final depth from the equation

In the current equation the pipe spacing depends on the discharge rate but in the new derived equation the pipe spacing depends on the final head. The effect of the upper layer thickness was added to the equation of the pipe discharge to increase the accuracy of the results.

The flux discharge of lowering the groundwater as computed by equation (6) is:

$$q = 0.003 \times k + 6.8E-07 \times L - 1.93E-05 \times th + 1.54E-04 \times h_o + 2.86E-05$$

q=0.58 mm/d

The inlet pipe discharge is = 97.5 mm/d/m =0.097m/d/m

16. Using the New Equations in the Design:

1. Determine the field measurements as the thickness of the upper layer, H.C. of the upper layer, and the initial head .
2. Select the final head at mid point between the drains .
3. Using equation (5) to design the spacing between the pipes .
4. Using equation (6) to determine the pipe discharge .
5. Design the diameter of the pipes .

17. Conclusions:

1. The new equations were derived to compute and design the drainage system depending on the thickness of a semi-pervious layer overlaying a coarse sand aquifer, upper layer soil H.C., the initial head, and the final head.
2. The equation of the discharge gives the actual pipe outlet discharge depending on the spacing between the pipes, upper layer soil H.C. and the thickness of this layer, the initial head, and the final head.
3. The new equations were compared with the current ones and field measurements which concluded that the new equations are simpler and gave similar results.
4. For the thin top thickness layer the new equations are more representative because the new equations depend on the thickness of the top layer.

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Dr. Amgad S. Elansary is a Professor of Hydraulics at the Department Of Irrigation & Hydraulics at the Faculty of Engineering, Cairo University .
He got his Ph.D from the University of Arizona and has over thirty (30) years experience in environmental management, design, project management, project identification, planning, implementation of activities, procurement, training, of multi-disciplinary environmental, sanitary and public works engineering projects, he also worked on development projects financed by International Lending Agencies, such as DANIDA, FINNIDA, KfW, USAID and others.

Dr. Ashraf M. Ghanem is an Associate Professor of Hydraulics at the Department of Irrigation and Hydraulics, Faculty of Engineering, Cairo University. He is also the deputy director of the Center of Studies and Designs for Water Projects, Faculty of Engineering, Cairo University. Dr. Ghanem received his B. Sc. in 1982 and M. Sc. in 1987 from the Civil Engineering Department, Faculty of Engineering, Cairo University, and his Ph. D. in Water Resources from the University of Alberta, Canada in 1995. His research interests include surface and groundwater and environmental hydraulics. He has supervised more than 20 M. Sc. and Ph. D. thesis in these fields. He is member of the Egyptian Syndicate of Civil Engineers, the Egyptian Water Partnership, the Egyptian Water Association, the World Aquaculture Society, the Egyptian Fish Council and the Egyptian Aquaculture Society.

Dr. Gamal H. Elsaeed is an Associate Professor at the Civil Engineering Department, Faculty of Engineering , Shobra, Banha University .
Dr. Elsaeed holds a B.Sc., M.Sc and Ph.D. in Civil Engineering from Ain Shams University and Texas A&M University . In addition to teaching undergraduate/graduate courses, supervising graduate students, he has published several research papers and attended several conferences in Egypt, U.S.A and Europe .
His research interests include Hydraulics, Coastal Engineering and Water Resources .
Dr. Elsaeed is a member of the Egyptian Society of Engineers and the American Society of Civil Engineers .
Dr. Elsaeed is a registered Consultant Engineer involved in several major projects in Egypt and the Middle East ranging from residential to infrastructure.

Dr. Neveen A. Badawy is an Assistant Professor of Hydraulics at the Faculty of Engineering, Shobra, Banha University . She got her Ph.D from Banha University in 2009 and her field of interest is Ground Water Engineering .