Mitigation of waterlogging problem in El-Salhiya area, Egypt

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ABSTRACT
The waterlogging problem was observed in El-Salhiya area, East Delta, Egypt, as a result of the rising water table in locations north of El-Salhiya canal and surrounding El-Heseneya canal. Therefore, the objectives are determining the causes of waterlogging depending on water quality and to mitigate the problem using the mathematical model. Results of water quality for surface and groundwater samples indicated that the waterlogging is mainly due to leakage of surface water from canals and drainage systems in the study area. The results of MODFLOW and MODPATH models approved that the problem was coming from the infiltration of water from the Ismailia canal and the irrigation network, in addition to excess irrigation water. Therefore, the main causes of the waterlogging problem grouped into two categories, natural and artificial. MODFLOW results showed that cutting drains with 2.5 m depth is the most effective method to mitigate the waterlogging problem.

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Introduction
In the former decades, groundwater development in Egypt has become more important. The occurrence of groundwater encouraged the government to construct new communities to overcome the growing population problem in Egypt (ElMahmoudi, Shendi, & Mohammed, 2006; Taha, El Mahmoudi, and El-Haddad (2005). Groundwater at a depth less than 6 m from the ground surface is called shallow groundwater (Hassan, 2006).

Excessive irrigation and lack of adequate drainage, in arid and semiarid zones, negatively affect agriculture production (Corwin, Rhoades, & Simunek, 2007). About a third of the world’s irrigated lands have decreased productivity as a result of badly managed irrigation that has caused salinization and waterlogging (Cirelli, Arum, Rivera, & Boochs, 2009).

Waterlogging refers to the fullness of soil with water, which used to define rising groundwater to surface level. Therefore, there are many efforts from researchers to study problems associated with reclamation projects on shallow groundwater level that cause waterlogging. Kaiser, El Rayes, Ghodeif, and Geriess (2013) stated that there is a positive relationship between agricultural reclamation along the extended desert fringes and waterlogging areas. Also, there are direct losses in crop productions and forgone profits as a result of the effect of, which significantly impact farmers (El-Nashar, 2013). The waterlogging problem could be overcome by using drainage systems (Mahmoud, 2017). Over the past decades, the role of drainage has improved from just objective measures for constraining salinity and/or waterlogging to an important part of integrated water management supporting multiple land use (Schultz, Zimmer, & Vlotman, 2007). In arid and humid zones, subsurface drainage used to prevent waterlogging and improve drainage to control salinity in the crop root zone (Valipour, 2014). To mitigate the effect of the waterlogging problem, there were long-term and short-term solutions. Long-term solutions include the construction of a sewage network in urban areas and lining the seepage reaches along canals. Short-term solutions include the construction of production well fields and construction of open drains.

The waterlogging problem was observed in El-Salhiya area, East Delta, Egypt (Figure 1). It is one of the desert settlements, land reclamation, and industrial projects. Therefore, the objectives of the present study are determining the causes of the waterlogging problem in El-Salhiya area depending on water quality and to simulate the groundwater aquifer with the help of a mathematical model to test proposed mitigation measures and identify the suitable solution of the waterlogging problem in the study area.

The studied area is located in the north of the Ismailia canal between longitudes 31° 30’ to 32° 20’ E and 30° 20’ to 31° N. (Figure 1). The main cities in the study area are Zagazig, Bilbeis, Abu Hamad, El-Tal El-Kebir, Al Qassasin, Abu Suweir, Ismailiya, Abu Kebir, Faqqs, El-Salhiya and Al Qantara. It is characterized by the semi-arid climate, where the average temperature ranges between 34 °C in summer to 8 °C in winter, the average annual rainfall is about 25 mm., the average humidity

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ranges from 45% in summer to 56% in winter, and the average evaporation ranges from 7 to 14 mm.

**Problem identification**

In 1981/82, reclamation works initiated with El-Salhiya Project in about 23,000 feddan (Meyer, 1998). The groundwater used as a potential source for irrigation and domestic water requirements. The waterlogging problem has occurred as a result of rising shallow groundwater reaching to or above the earth surface. The depth to groundwater was varied from 1 m north of El-Salhiya to 20 m near Ismailia Canal and the depths at New El-Salhiya ranged from 1.3 to 18 m, while the water level ranged from 2.19 to 9.31 m (Rizk, 1997). The agricultural activities and irrigation system have a great impact on groundwater levels and water quality of the Quaternary aquifer in El-Salhyia area (Mabrouk, Ramadan, Nagaty, & Abd El Azeem, 2016). The good drainage system should be constructed in areas suffering from waterlogging to dewater the excess irrigation water and protect the old cultivated land from destruction (Dahab, Omran, Abdalall, & Alkilany, 2009). The source and amount of recharge, type of sediments, and groundwater flow are mainly affecting the geochemical properties of the Quaternary aquifer in El-Salhiya plain.

*Figure 1. Location map and satellite image of the study area (by Google Earth).*
Topographical data were retrieved from DEM file covering the study area. The ground elevation varies from the highest more than 40 m + msl, in the south to the lowest about 2 m. +msl in the north (Figure 2). Based on observation well, a map of groundwater depth was drawn showing that the groundwater table depth ranged from less than 0.5-m depth from the ground surface to more than 2 m (Figure 3). The groundwater table depth is increasing south of El-Salhiya canal where the ground surface is high as shown from the topographic map. These maps give a clear identification of the affected locations by waterlogging problem in the study area. These locations include north of El-Salhiya canal and surrounding El-Heseneya canal (Figure 3).

Materials and methods

To reach the objectives, geological and hydrogeological data have been collected and used for understanding groundwater aquifer system features in the study area. Water samples from wells, canals, and drains have been collected and chemically analyzed for the determination of the genesis and sources of the waterlogging problem. Numerical models have been prepared for simulating the aquifer system and tracking the source of seepage water. In this study, Visual MODFLOW numerical model package used to simulate groundwater aquifer system in the study area. It is a groundwater model based on the finite-difference technique (McDonald & Harbaugh, 1988). MODPATH is a particle-tracking model used to compute flow paths using the calibrated model output from the Visual MODFLOW model (Pollock, 2017). Therefore, MODPATH particles used in tracking the source of seepage water. Proposed mitigation measures are tested by the model to predict its effect to apply for solving the waterlogging problem in the study area.

Hydrogeology and land use

The Nile passed through five main episodes since the valley was cut down in late Miocene geological time since about 15 million years ago (Said, 1990). These five rivers are Eonile (Tmu), Paleonile (Tplu), Protonile (Qn1), Prenile (Qn2), and Neonile (Qn3). Each of these episodes was characterized by a master river system. Toward the end of each of the first four episodes, the river seems to have declined or ceased entirely to flow into Egypt. The Quaternary deposits (Qn1, Qn2, Qn3) constitute the bulk of the main aquifer in the
study area. Formations are mainly composed of loose sand with different proportions of pebbles and gravels (Figure 4). Clay sheets and lenses intercalations are present at different depths (Figure 5). The greatest thickness of the Quaternary deposits in the study area is about 600 m resting unconformably on Pliocene clay or Miocene sandstone and limestone (Figure 5).

The Miocene deposits; of sand, sandstone and gravel with clay, marl or limestone interbeds are present in the subsurface of the study area forming different formations named Hagul, Homath, and Sadat Formations (Said, 1990; EGPCO (The Egyptian General Petroleum Corporation), CONOCO (Conoco Coral), 1987). They overlie unconformably the Oligocene deposits of sands and gravels (Figures 4, 5). The studied area has been subjected to different types of faults which have been affected greatly the hydrology of the present aquifers and the thickness of the sedimentary column.

The Quaternary aquifer is the most important as a groundwater source for irrigation and drinking water in the study area (Figures 4, 5). This aquifer consists of Pleistocene sand and gravel sediments with a thickness of
about 200 m in the south increasing northward reaching about 600 m (Figure 5). The groundwater aquifer in the study area is leaky (unconfined) aquifer in the southeast and becomes semiconfined in the northwest where a semipervious clay cap layer is present. The lower part of the Quaternary aquifer constitutes the Plio Pleistocene sediments of mixed shale, sand and gravel (RIGW/IWACO, 1998; Mabrouk et al., 2016). The aquifer is recharged mainly by the seepage from different water channels in the area (canals and open drains) and the excess irrigation water in the agricultural lands. The Miocene and Oligocene aquifers are present in the subsurface under the quaternary aquifer (Figure 5).

The Ismailia canal is the main source for freshwater from which other distributary canals take their water as El-Salhiya canal, El-Samaania canal, Bahr Moweis canal, El Saidiya canal, El Tolombat canal, El Heseneya canal and Port Said canal. Main open drains are present such as Bahr El-Baqar drain and El Arein drain. The most populated areas are Zagazig, Billeis, Abu Hamad, El-Tal El-Kebir, Al Qassasin, Abu Suweir, Ismailiya, Abu Kebr, Faqus, El-Salhiya, and Al Qantara cities. The main source for drinking and industrial water purposes is the groundwater. The study area has been planned for great development including many of the reclaimed agricultural lands and industrial areas that are under construction (Figure 6).

**Numerical simulation model**

**Model development**

Prior to preparing a numerical model, first, a conceptual model was developed to understand the groundwater aquifer system in the study area. To develop conceptual model data necessary for the simulation process were collected to define the top and bottom levels of the aquifer, geological layers type, hydraulic parameters for layers, location of rivers, canals, drains, wells, and model boundary conditions. To present the variation in Lithology the model consists of three layers representing the aquifer system. The first layer simulated the clay cap that covered the aquifer in the northern part of the study area with a thickness of about 15 m. The second layer simulated the main extraction zone of the aquifer where screens of the production wells were situated. The third layer simulates the lower part of the aquifer. Once the conceptual model created, it was transformed into a numerical model by generated a grid.

The simulation process started by dividing the study area into a grid of rectangular cells (Figure 7), where each cell...
model layer consisting of 379 columns and 184 rows. Boundary conditions selected far from the effect of any activities in the study area depending on the natural hydrogeological situations (Figure 7). The modeled area surrounded by Ismailia canal from the south, Port Said canal from the east, El-Saideya Canal from the west and northwest. These canals are considered as river boundaries using the average water levels. The Ismailia canal was added as a river boundary using an average depth of 4 m (Gad, ElKammar, & Ismail, 2015). The northern boundary match average piezometric headline 4 m (+msl), therefore it considered as constant head boundary. (RIGW, 1992). Topographical data were added from the DEM file covered the modeled area (Figure 2). The recharge zones defined depend on the landuse and hydrogeologic conditions for each zone in the modeled area. Groundwater recharged by seepage from canals and irrigation network, through downward infiltration from excess irrigation water, rainfall during winter, and inter-aquifer flow (RIGW, 1992).

The quaternary aquifer composed of sand and gravel sediments covered by semi-confining aquitard clay cap layer in the northern part of the study area. The hydraulic parameters, required for simulation each layer, include the horizontal and vertical hydraulic conductivity, storativity, specific yield and porosity. These initial input hydraulic parameters are based on the RIGW database and previous studies (RIGW, 2002).

**Model calibration**

Calibration process was carried out by changing the hydraulic parameters and recharge rate through several trials. Calibration achieved when the error within the estimated error interval 95% of the observed value (Figure 8). Groundwater heads for 14 observation wells used for the calibration process. Where points that plots on or close to the diagonal line indicated low error within the allowed interval and points far from diagonal have a larger error. The calibrated hydraulic parameters for the semi-confining layer have a hydraulic conductivity ranged between 0.1 and 0.25 m/day, the hydraulic conductivity of the quaternary aquifer ranged from 30 to 100 m/day, the specific storage of the quaternary aquifer is about $6 \times 10^{-7}$, and the specific yield ranged from 0.10 to 0.20. Figure (9) shows calibrated piezometric contour map and the velocity vectors. The main groundwater flow direction is from south to north with an average groundwater velocity about 0.037 m/day. The groundwater levels ranged between 8.5 m + msl in the south and 4 m + msl in the northern part of the study area.

**Results and discussion**

**Genesis of water**

The Piper diagram (Piper, 1944; Freeze & Cherry, 1979) of the study area shows that there is a good relationship between the surface water and groundwater (Figure 10). Groundwater wells surrounding the course of canals indicate recharge from these canals with water dominated by alkaline earth and weak acids, i.e. mainly calcium and magnesium bicarbonate water type. Other samples are plotted in area right of the Piper diagram indicating dominantly strong acids in groundwater and drainage water source (i.e. mainly sodium chloride and sulfate water type). Some wells indicate recharge from another third source as the intrusion of saline groundwater from the Suez canal. Groundwater in these wells is dominated by alkalies and strong acids, i.e. mainly sodium chloride and sulfate water type.

The Schoeller diagram (Schoeller, 1969; Freeze & Cherry, 1979) is used to study the comparative changes in the concentrations and ratios of water quality parameters for different samples (Figure 11). Samples with similar source connecting with lines of parallel slope. Results specify that water samples divided into two types on the basis of calcium (Ca), sodium (Na), chloride (Cl), and bicarbonate (HCO$_3$) contents. The most water type of high sodium content also has a high concentration of chloride content indicating sodium...
chloride water type due to recharge from saline water and leaching processes. Some other samples contain high calcium and high bicarbonate indicating calcium bicarbonate water type due to recharge by freshwater from canals and excess irrigation water.

**Numerical simulation model results**

The calibrated model provided an understanding of the groundwater flows through the aquifer system. The groundwater levels change from about 8.5 m + msl near Ismailia canal and decrease northward until reaching about 4 m + msl near the El-Hesanya Canal (Figure 9). It could be understood that the Quaternary aquifer in the study area was recharged mainly from infiltrated water from canals network and excess irrigation water. The calibrated MODFLOW flow model used for the particle tracking MODPATH simulation. MODPATH tracks the flight of groundwater particles due to advective groundwater flow from defined starting locations. Backwards particle tracking using MODPATH was used to determine the source of where recharge coming from to waterlogging locations (Figure 12). Pathlines map represents a historical travel record of the groundwater particles (Pollock, 2016). These pathlines determine and presented the capture zone of the waterlogging area. It could be
Figure 10. Piper diagrams for the water samples.

Figure 11. Schoeller diagrams for the water samples.
concluded that the causes of the waterlogging problem in the affected locations were the seepage water from the Ismailia canal, from other canals network and excess irrigation water.

Testing proposed mitigation measures

The calibrated MODFLOW model was used to test different proposed solutions. The first short term by using vertical drainage solution needs to construct 94 production wells in and around the affected locations. Three pumping rates were tested 30 m$^3$/h, 40 m$^3$/h, and 50 m$^3$/h. The results indicated that the minimum depth to groundwater table that could be reached is about 0.5 m (Figure 13(a–c)).

The second short-term solution is proposed the construction of cutting drains. Three scenarios were tested by the calibrated model.

First, drain depth 1.5 m and gravel filter permeability coefficient 30 m/day,

Second, drain depth 1.5 m and gravel filter permeability coefficient 50 m/day and

Third, drain depth 2.5 m and gravel filter permeability coefficient 50 m/day.

The results indicated that the minimum depth to groundwater table that could be reached exceeds 1.0 m below the ground surface (Figure 14(a–c)).

Conclusion and recommendations

The groundwater levels in El-Salhiya area change from 8.5 m + msl in the south near Ismailia canal and decrease northward until reaching 4 m + msl in the north of the study area. The locations affected by waterlogging located in the low topographic levels land north El-Salhiya canal and surrounded El-Heseneya canal.

The hydrochemical and numerical models result indicated that the study area waterlogging problem was mainly originating from a mixture of different sources including freshwater seeped from canals and excess irrigation water; agricultural drainage water; wastewater from sewage drainage systems and septic tanks; intruded saltwater from Suez canal and dissolution of salts from soil and aquifer sediments.

MODFLOW and MODPATH model results showed that the groundwater flow in the study area is mainly from south-to-north direction with an average flow velocity of about 0.037 m/day. The groundwater in the Quaternary aquifer is recharged essentially from the infiltrated water from the Ismailia canal, El Salhiya canal and their tributaries and excess irrigation water.

Therefore, there are natural and artificial causes of the waterlogging problem in the study area. Natural causes include topography and geological sediment characteristics of the waterlogged locations. Artificial causes include seepage water from canals, excess irrigation water, and sewage drainage water.

A quick solution for the waterlogging problem in the study area requires the implementation of about 94 production wells and needs high operational and maintenance costs. Therefore, short-term solution using pumping wells was refused. Cutting drains around the affected locations with 2.5 m depth and permeability coefficient 50 m/day is the most suitable and
effective mitigation measure for solving the problem because it is lower in operational and maintenance costs.

From the results, the following was recommended:

- Construction of a sewage network in urban areas and lining the seepage reaches along canals as a long-term solution for the problem.

Figure 13. (a) Groundwater table depth due to testing pumping wells (30 m³/h). (b) Groundwater table depth due to testing pumping wells (40 m³/h). (c) Groundwater table depth due to testing pumping wells (50 m³/h).
- Construction of cutting drains with 2.5 m depth and permeability coefficient 50 m/day around the affected locations.
- Replacement of traditional irrigation by modern irrigation systems to limit water from infiltration and seepage to the low-topographic land.
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