Simulation of groundwater fluctuation for Baghdad City and its effect on soil properties

R H Irzooki¹, A A Al-Obaidi² and H F Al-Dulaimy²

¹ Environmental Engineering Dept., Engineering College, Tikrit University, Salah Aldeen, Iraq
² Civil Engineering Dept., Engineering College, Tikrit University, Salah Aldeen, Iraq

Email: dr.ahmed64@gmail.com

Abstract. Baghdad city is one of the most densely populated cities in the Middle East. The fluctuation of the groundwater in Baghdad city is due to leakage of water from distribution networks or sewage networks, as well as climate change and the existence of the Tigris River. The groundwater level in Baghdad city was simulated using the MODFLOW program, based on Tigris River as the main source of groundwater recharge by raising the water surface of this river to the maximum level, which reached 32.44 meters above sea level. In addition, soil properties of 262 sites were linked to the groundwater level fluctuation through the GIS program. It was found that the river fluctuation affects the groundwater level on both sides of the river for a distance about 500m from the riverbank in Al-Karkh side and about 550m in Al-Rusafa side. Also, from the simulation process, the study found that the soil on both sides of the Tigris River is divided into three zones; dry, partially saturated, and fully saturated in the areas near the river. A new relationship between the volumetric water content and shear strength parameters ($c_u$ and $\phi$) were developed for adjacent zones to the river.

1. Introduction

The nature of Baghdad groundwater is complex, where it is fluctuates through the year due to the increase in the industrial, municipal, and agricultural activities, the leakage from water distribution networks or sewage networks, as well as climate change. All these factors, besides the existence of Tigris River, have made the process of controlling the rise of groundwater relatively intricate. These conditions require considerable efforts by the specialists in the fields of geotechnical engineering, hydrology, hydrography, hydrochemistry and geochemistry. Groundwater movement system in Baghdad area represents part of the general movement system of the Tigris basin, considering Tigris and Diyala rivers as the discharge zone in general, as shown in figure 1. The groundwater levels in Baghdad city range between (25 –36) m above sea level, and it is noticed that there is an increase in the value of the hydraulic slope, clearly north of the governorate, probably as a result of little permeability of the area rocks.

The eastern areas of Baghdad are recognized by the dropping of their groundwater levels compared to those of the western areas; this is why the flow is going to be from west to east and southeast. In contrast, the presence of the rivers (Tigris, Diyala and the Euphrates), which represent important hydrogeological borders for aquifer systems, especially in Quaternary sediments led to the appearance of local movements due to the hydraulic connection between those rivers and groundwater recharge and discharge, [1].

2. Simulation of Groundwater
The first time, analytical solutions for groundwater was done by Toth, [2] to investigate groundwater flow in hypothetical small drainage basins. The application of groundwater flow models to large-scale aquifer system simulation started in 1978, with the Regional Aquifer-System Analysis (RASA) program, [3]. In Iraq, Salman et al., [4] conducted a detailed study on groundwater and engineering properties of soil. The Computer-based numerical groundwater flow models were constructed and used to characterize flow systems and to simulate the effects of groundwater development and land use changes. Computer models used in most cases were the USGS 3D finite difference model and the USGS MODFLOW, [5]. Significant advances in system analysis the groundwater flow were driven by several software codes, such as FEFLOW, SVFlux, FEHM, HydroGeoSphere, OpenGeoSys, and ZOOMQ3D.

Since its release in 1988, MODFLOW has become the industry standard worldwide for groundwater modelling because of its flexible modular structure, complete coverage of hydrogeological processes and public domain free availability, [3]. Since then, the MODFLOW software has been utilized in the design, prediction of groundwater level, simulation of water level in rivers and reservoirs, [6], [7], and [8].

Through a search in literatures [1], [4], and [6], it can be concluded that the level of water in the Tigris River is considered as the main influencing factor on the groundwater table in Baghdad city. The rest of the water clusters may be variable and may disappear with the development of the city. Therefore, this study will focus on the use of the MODFLOW program to simulate the variation of groundwater table as a function of the water level in the Tigris River. In addition, the GIS program will be used to describe the soil properties of Baghdad city and developing relationships for the effect of groundwater level fluctuation on the geotechnical properties for Baghdad soils.

3. Data Acquisition and Analysis

The study area, which is located in the centre of Iraq represents the urban areas of the Baghdad city. This area was divided into two regions (Al-Karkh and Al-Rusafa) in the MODFLOW program to obtain higher accuracy of the results.

The first phase of any groundwater study consists of collecting all existing geological and hydrological data on the groundwater basin in question. The groundwater balance or numerical model requires a set of quantitative hydrogeological data that fall into data that describe its hydrological framework and data that define the physical framework of the groundwater basin. For the hydrological framework, essentially, two types of data must be input to the program, the first one is the groundwater table elevation, and these data were collected carefully from field data for 30 wells measured in May 2010 by [9]. The second is the elevation of the Tigris River, which was collected from the measurement of the Sarai station in Baghdad city. ‘Figure 2’ shows the distribution of wells in the study area.

The elevation of the water level of the Tigris River considered as the ruling of the groundwater elevation. The maximum and minimum levels of the river are taken during the last years (1990-2011) as mentioned by the Iraqi Ministry of Water Resources. The minimum level of the river at the Sarai station was 28.17m, which is approximately considered as the minimum level of the river in previous years, i.e., the minimum level possible to drop for the river, the level of the river was raised to the maximum level that can be reached at flooding wave occurrence, which is 32.44m.

According to data obtained from Ministry of Water Resources, the average of hydraulic conductivity was 6m/day recorded in 2004, while Al-Jiboury, [10] considered that the value of hydraulic conductivity range between (1.55 - 2.16) m/day. Throughout several trials, it has been found a value of 4 m/day for the hydraulic conductivity obtained reasonable results. The specific yield value
almost recorded from the monitoring wells; this value is taken as $3 \times 10^{-3}$ for clay soil since most of Baghdad soil consists of lean and fat clay, [11].

The top aquifer was taken as 34m. It is the same as the maximum value of the head, and the bottom aquifer is 4m, so the depth of aquifer is 30m. The aquifers considered as confined and semi-confined. Thus, the layer is taken varied in the simulation. As the value of hydraulic conductivity is considered as an input data and the program calculations based on it, thus, the transmissivity considered as a non-ruling variable. In the MODFLOW program, there are two types of cells that control the process of simulation, non-active cells that mean no flow and active cells that mean a flow. The Model Discretization is utilized to divide the study area (for Al-Karkh region and Al-Rusafa region) into a grid of rows and columns and to clarify the boundary conditions. The mathematical model’s philosophy is based on differential equations in the use of the smallest possible model for the formation of the block or grid. Although there are several types of grid, the block-centred is the most appropriate method in finite difference due to it is suitability for the area in which the flow is described. It also has the ability to treat boundary conditions easily, [12].

![Figure 1. Hydrogeological map of the Baghdad Governorate, shows static water level and direction of ground, [1].](image1)

![Figure 2. The distribution of wells in the study area.](image2)

The size of the grid has a great effect on the success of simulation; so many trials have been done to obtain the appropriate size. Initially, the area was divided into 20 rows ($\Delta y=1132$ meters) and 20 columns ($\Delta x=1010$ meters). Then, the number of columns and rows was doubled to 40 columns and 40 rows. In the last trial, the number of rows was 160 and the number of columns was 160. From the trials, it is found that 80 rows ($\Delta y=283$ meters) and 80 columns ($\Delta x=252$ meters) is the best division for the region since there is no considerable difference between it and the subsequent trials.

Model Calibration was utilized to ensure correct results from the simulation; it must be a correspondence between the observed water levels and the calculated water levels of the program, [12]. The Tigris River was considered as the source of recharge by a flood wave causing a rise in the river level, leading to a clear change in the groundwater levels in the areas near to the river. Thus, the river becomes a source of recharge for groundwater in the areas near the riverbank.

The results obtained from the program considering the input data and modelling revealed that there is a clear effect of the water level in the Tigris River on the groundwater level. The variation of the
The groundwater level is evanesced as moving away about 500m from the river edge for Al-Karhk region and 550m for Al-Rusafa region as shown in ‘Figure 3’.

The direction of groundwater flow is perpendicular with head equipotential; also, the flow of groundwater is toward the Tigris River, especially at nearby areas. The direction of the groundwater movement also coincides with the downward trend in the surface level of the earth in general, which descends towards the south and southeast for Al-Karhk region and southwest for Al-Ruafa region.

4. Simulation of the Soil Geotechnical Properties
To study the effect of groundwater level variation on the soil characteristics, the soil properties of the Baghdad city was simulated using the GIS program. This program allows modelling the natural variation of soil conditions and the effects of various factors on material resistance. The main sources of data were collected from soil investigation reports, (carried by National Centre for Construction Laboratories and Research NCCLR, [13], and Andrea Engineering Testing Laboratory, AETL [14]) beside the data accumulated from Al-Adili, [15], and Safaa, [16].

\[\text{Figure 3. Cross-section shows drop in effect of groundwater for (A) Al-Karhk region and (B) for Al-Ruafa Region}\]

The data are accumulated from 262 boreholes distributed at Baghdad city for various type of projects. ‘Figure 4’ shows the distribution of borehole locations in the study area.

From the results obtained using the MODFLOW program after considering the highest level of the Tigris river is 32.44m above sea level, and the lowest level is 28.17m, it can be seen that the impact of the variation in the groundwater level in Baghdad as shown in ‘Figure 5’, this figure is a modification of ‘Figure 1’ considering that the part of the groundwater level of the two sides of Al-Karhk and Al-Ruafa regions which not affected by the changing the water level in the Tigris River is a reference line, the elevation of this line is zero. The main goal for this issue is to diminish the impact of different levels of the natural land of Baghdad city and to achieve the objective of this study.

Thus, the maps produced in the GIS program will be divided as follows: The first layer is taken above the maximum groundwater level. In this layer, the data taken into account is only for the two meters above the maximum groundwater level and the invariable groundwater level, where the data sources considered that the soil layers above this is fill material (human-made) and must be removed.
before starting construction. The second, third, and fourth, layers are taken with 2m thickness for each one, respectively. All these layers are under the maximum groundwater level. From ‘Figure 5’, it is clear that any soil below the fourth layer, (i.e., more than 6m beneath the maximum groundwater level) is almost fully saturated and will not be affected with the variation of groundwater level.

![Figure 4. Location of boreholes in Baghdad city.](image)

![Figure 5. Maximum and minimum groundwater levels at Al-Kharkh and Al-Rusafa regions.](image)

5. **Physical and Engineering Soil Properties of Baghdad City**

The soil type of Baghdad city is classified according to the Unified Soil Classification System (USCS). ‘Figure 6’ shows the variation of soil starting from 2m above maximum groundwater level (i.e., layer one) down to 6m beneath the maximum groundwater level (i.e., layer 4). Most of the first layer contains a lean clay (group symbol is CL). In the second layer (0-2m beneath the maximum and invariable groundwater level), the fat clay (group symbol CH) becomes the most widespread than the lean clay (CL), it covers about more than 60% of the study area, and the silt and sand represent a small proportion. In the third layer, (2-4) m beneath the maximum and invariable groundwater level, clayey soil is predominant in the study area; it is shown that the lean clayey and fat clayey soils represent the largest proportion of soil in the region with a small amount of sand and silt. The fourth layer (4-6) m beneath the maximum and invariable groundwater level, shows the predominance of clayey soil also. However, silty sand and sandy soils are beginning to show more, especially in the Al-Karkh region.
Moisture content defined as the amount of water contained in a particular mass or volume of soil and is considered to be directly affected by groundwater. This property changes over time as a result of other properties and circumstances. The following ‘Figure 7’ shows the change of moisture content with depth in Baghdad city. Starting from the first layer, the value of the moisture content ranges between 21% to 28% except for some areas in the southeast where the value is less than 20%. In the second layer, the value ranges from 20% to 30%. Most of the study area in the third layer has values of water content ranging between 20% to 30%. However, for the fourth layer, the value of moisture content ranges between 23% to 33%. From the preceding maps, it can be noticed that the value of moisture content increased with depth, where the soil is under the groundwater.

‘Figure 8’ indicated that the dry unit weight was ranging between 15 kN/m$^2$ to 17 kN/m$^2$ in the first and second layer. It decreases in the values at third layer and ranges between 15 kN/m$^2$ to 16 kN/m$^2$ in most of the study area except at the eastern part where the value is greater than 16 kN/m2 and some areas in the northern and southern part has a value less than 15 kN/m$^2$. In the fourth layer, the value ranges between 14 kN/m$^2$ to 16 kN/m$^2$ except for eastern part from Al-Rusafa side that value was greater than 16 kN/m$^2$ and some areas in the north western and south western part have a value less than 14 kN/m$^2$. The values of the dry unit weight are reasonable where the clayey soils give values higher than the silty sand soils.

‘Figure 9’ shows the values of the unconfined compressive strength ($q_u$) of soil for Baghdad city through the four layers considered. For the first layer, it can be observed that the values of the ($q_u$) ranged between 100 to 170 kN/m$^2$, i.e., the soil can be considered as a medium to stiff clay in consistency. In the second layer, the unconfined compression strength ranged from 100 kN/m$^2$ to 260 kN/m$^2$. At Northwest, the unconfined compressive strength indicates that the soil is stiff, while it gives some high values (more than 300 kN/m$^2$) at the south eastern part. For the third layer, it can be observed that the value of ($q_u$) ranged from 100 to 200 kN/m$^2$. In the fourth layer, the soil can be considered as a medium to stiff clay in consistency.

The internal friction angle is illustrated in ‘Figure 10’. For the first layer, it can be observed that the values of the internal friction angle tend to be low in the northern part of the region and tend to be intermediate in the centre and southern part. An increase in internal friction angle in Al-Rusafa region for second and third layers, while different value has been found in the study area following the soil type. The high value in internal friction angle and unconfined compressive strength show that the soil has been subjected to compression due to the implementation of the facilities in earlier times and near the layer of the surface of the earth and thus, water evaporates and increases the strength of the soil.

### 6. Influence of groundwater level on the soil properties

To discuss the influence of groundwater level on the soil properties in Baghdad city, it is reasonable to consider two zones. The first one is near the riverbank (i.e., 500m from the river at Al-Karkh region and 550m at Al-Rusafa region), while the second zone lies after the first zone and on both sides (Al-Karkh and Al-Rusafa), it can be called the invariable groundwater level zone. However, the first layer represents dry soil that extends from ground level to maximum water table while the fourth layer represents saturated soil that lies below the minimum water table. Thus, the second and third layer represent the case where the soil properties will change of it’s the degree of saturation following the fluctuation of water table which extends from the maximum groundwater level to the minimum groundwater level.

### 7. Correlations between the variation of groundwater level and engineering soil properties

For devising a relationship between the amount of water in the soil due to groundwater variation and its engineering properties, it is logical to choose soil properties such as dry unit weight, specific gravity, etc. These parameters do not depend on the amount of water in the soil. Thus, the parameter
named volumetric water content ($\theta_v$) is used and correlated with the soil engineering properties. The volumetric water content is defined as shown in equation (1) [17], [18].

**Figure 6.** Soil type for Baghdad city, (A) above Maximum and invariable groundwater level, (B) (0-2m) beneath the Maximum and invariable groundwater level, (C) (2-4m) beneath the Maximum and invariable groundwater level, and (D) (4-6m) beneath the Maximum and invariable groundwater level.

**Figure 7.** Soil moisture content (%), (A) Above Maximum and invariable groundwater level, (B) (0-2m) beneath the Maximum and invariable groundwater level, (C) (2-4m) beneath the Maximum and invariable groundwater level, and (D) (4-6m) beneath the Maximum and invariable groundwater level.
Figure 8. Dry unit weight (kN/m$^3$), (A) Above Maximum and invariable groundwater level, (B) (0-2m) beneath the Maximum and invariable groundwater level, (C) (2-4m) beneath the Maximum and invariable groundwater level, and (D) (4-6m) beneath the Maximum and invariable groundwater level.

Figure 9. Unconfined compression strength of soil (kN/m$^2$), (A) Above Maximum and invariable groundwater level, (B) (0-2m) beneath the Maximum and invariable groundwater level, (C) (2-4m) beneath the Maximum and invariable groundwater level, and (D) (4-6m) beneath the Maximum and invariable groundwater level.
Figure 10. Angle of internal friction of soil (°), (A) Above Maximum and invariable groundwater level, (B) (0-2m) beneath the Maximum and invariable groundwater level, (C) (2-4m) beneath the Maximum and invariable groundwater level, and (D) (4-6m) beneath

\[
\theta_v = \frac{\gamma_i \cdot e \cdot s}{G_s \cdot \gamma_w} 
\]

(1)

Where:

- \( \theta_v \): Volumetric water content,
- \( \gamma_i \): Soil Unit Weight,
- \( e \): void ratio,
- \( s \): degree of saturation,
- \( G_s \): specific gravity, and
- \( \gamma_w \): unit weight of water

In addition, the correlations are developed depending on the soil type found adjacent to the banks of the Tiger River, i.e., lean clay (CL), fat clay (CH), and silty sand soil (SM).

For the area of lean clay soil, a dependable nonlinear relationship between undrained shear strength at this area and correlated to the volumetric water content has been obtained as defined in 'equation (2)'.

\[
\theta_v = 0.6434C_u^{-0.119} 
\]

(2)

A fear relationship has been found between the volumetric water content and angle of internal friction for lean clay soil zone, as shown in 'equation (3)'.

\[
\theta_v = 0.4336\phi^{-0.066} 
\]

(3)

For soils of fat clay (CH) near the Tiger River banks, the data collected gives a relationship between the volumetric water content and undrained shear strength, as shown in 'equation (4)'.

\[
\theta_v = 0.4652C_u^{-0.046} 
\]

(4)

The angle of internal friction can be estimated from 'equation 5'.

\[
\theta_v = 0.537e^{-0.022\phi} 
\]

(5)
In the area of silty sand soil (SM), an excellent correlation has been found between the volumetric water content and the angle of internal friction, as shown in 'equation 6'.

$$\theta_v = 0.0003\phi^2 - 0.0165\phi + 0.5851 \quad (6)$$

The present empirical equations to predict the component in the shear strength of unsaturated soils as an exponential function of volumetric water content seems to be reasonable. Where there is a reduction in the engineering soil properties (i.e., $C_u$ and $f$) as the degree of saturation considered in the volumetric water content increased. The methodology described in this study provides a convenient alternative to the quantitative estimation of unsaturated shear strength, as no matrix suction data are required.

8. Conclusions
From the results obtained using MODFLOW and GIS programs considering only the effect of Tigris River on the fluctuation of groundwater level and its effects on engineering properties of soil in Baghdad city, it can be concluded that there is a clear effect of Tigris River water level on the groundwater level at Al-Karkh side for about 500m from the river edge. At Al-Rusafa side, it seems that the Diyala River had a limited impact on the groundwater variation. Therefore, the Tigris River becomes the main source of recharge for groundwater in the areas near the river bank. So, the obtained results indicate that the clear effect of the variation of the Tigris River on the change of the groundwater level in this side is impacted within only about 550m from the river edge.

The flow of groundwater in Baghdad city is generally towards the Tigris River, and this river is considered as affluent in normal conditions because the river level is in the period of drought condition. When the flood conditions occur and the Tigris River rises to maximum level, the river becomes an influent for the areas adjacent it because of the proximity of the river with the groundwater level in these areas. The direction of the movement of groundwater also coincides with the downward trend in the surface level of the earth in general, which descends towards the south and south-east in Al-Karkh side and south-west in Al-Rusafa side.

The empirical equations predicted from this study provides a convenient alternative to the quantitative estimation of unsaturated shear strength, as no matrix suction data are required.

References
[1] Al–Basrawi N H, Awad J H and Hussain T A 2015 Evaluation of the groundwater in Baghdad governate / Iraq Iraqi Journal of Science 56(2C) pp 1708-18
[2] Toth J 1963 A theoretical analysis of groundwater flow in small drainage basins Journal of Geophysical Research 68(16) pp 4795-4812
[3] Zhou Y and Li W 2011 A review of regional groundwater flow modelling Geoscience Frontiers 2(2) pp 205-14
[4] Salman A, Sultan S A and Ibrahim I M 1990 Study of Water Table Level and Engineering Properties of Soil in Baghdad City (Amanat Baghdad, Directory of Laboratories, Designs Section, Iraq)
[5] McDonald M G and Harbaugh A W 2003 A Modular Three-Dimensional Finite-Difference Groundwater Flow Model (Techniques of Water-Resources Investigations of the United States Geological Survey USGS Science for a Changing World) p 588
[6] Ali S M 2012 Hydrogeological Environmental Assessment of Baghdad Area (Ph.D. Thesis, Department of Geology, College of Science, University of Baghdad, Baghdad, Iraq)
[7] Al-Jubouri M A 2011 Evaluation of Hydrogeological Conditions, and Mathematical Modeling of Aquifer in the Location of Hatra Suggested Dam (M.Sc. Thesis, Department of Geology, College of Science, Tikrit University, Iraq)
[8] Wang S, Shao J, and Song X 2008 Application of MODFLOW and geographic information system to groundwater flow simulation in North China Plain, China, *Environ Geol.* **55** 1449
[9] Tahir R K 2013 Mapping and Analyzing Contour Maps of Groundwater Levels for a Part of Baghdad City (M.Sc. Thesis, Department of Surveying Engineering, University of Baghdad, Iraq)
[10] Al-Jiboury H 2009 *Hydrogeological Conditions in Baghdad Governorate* (GEOSURV, report No. 3163, Baghdad, Iraq) p 54
[11] Todd D K and Mays LW 2003 *Groundwater Hydrology* (Wiley International Edition 3rd edition) p 625
[12] Langevin C D, Gualbert H P, Oude E, Sorab P and Barcelo M 2004 MODFLOW-based tools for simulation of variable-density groundwater flow, *In book: Coastal Aquifer Management-Monitoring, Modeling, and Case Studies* (Publisher: Lewis Publishers, Editors: Alexander Cheng, Driss Ouazar).
[13] National Center for Construction Laboratories and Research NCCLR, *Site Investigation Reports*
[14] Andrea Engineering Testing Laboratory AETL, Iraq *Site Investigation Reports.*
[15] Al-Adili A S 1998 *Geotechnical Evaluation of Baghdad Soil Subsidence and their Treatments* (Ph.D. Dissertation, College of Sciences, University of Baghdad, Iraq)
[16] Safaa J W 2017 *Geotechnical Study of Baghdad Soil with Evaluation of Liquefaction Potential* (M.Sc. Thesis, University of Technology, Building and Construction Engineering Dept. Iraq).
[17] Al-Obaidi, A H Fattah, M Y and Al-Dorry M Kh 2018, Variation of suction during wetting of unsaturated collapsible gypsumous soils, *International Journal of Engineering & Technology*, 7 (4.37) pp 79-85
[18] Matsushi Y and Matsukura Y 2006 Cohesion of unsaturated soils as function of volumetric water content, *Bull Eng. Geol. Env.* **65** pp 449-55