NUMERICAL ANALYSIS TO ASSESS THE IMPACTS OF CHANGING GROUNDWATER LEVELS ON LAND SUBSIDENCE

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ABSTRACT

Groundwater provides about one-third of the world's drinking water. Excessive abstraction from groundwater aquifers resulting in decline in groundwater levels that may lead to compaction of aquifer and land subsidence. Land subsidence has many damages effects such as; damage to bridges, highways, buildings, sewers, canals and embankments. Management of abstraction to avoid land subsidence is an important issue. This study aims to assess the effect of increasing pumping rates on land subsidence and determine relation between change in groundwater level and land subsidence. MODFLOW is used to simulate groundwater flow. A number of scenarios for different abstraction rates have been studied. Also, the effect of changing the aquifer properties due to settlement such as hydraulic conductivity, specific storage and porosity have been studied. Analytical solution has been developed to determine the settlement in the soil related to change in groundwater levels for each case. The developed model has been applied to a hypothetical case study. The results revealed that increasing abstraction rates has increased both drawdown and land subsidence. However, changing aquifer properties gave different effects on drawdown and land subsidence. Decreasing the aquifer hydraulic conductivity led to increase the drawdown and land subsidence, decreasing specific storage has no effect on drawdown but increased land subsidence but changing the porosity has no effect on both drawdown and land subsidence. This reveals that, the groundwater abstraction rates should be controlled to reduce land subsidence and protect infrastructures from anticipated damages.

Keywords: Groundwater, over-pumping, aquifer properties, land subsidence, MODFLOW.

1 INTRODUCTION

Land subsidence is a gradual settling or sudden sinking of the Earth's surface owing to rearrangement of the soil grains. Land subsidence occurs due to several causes such as aquifer system compaction, oil and gas field withdrawal, drainage of organic soils, natural sediment compaction and geotectonic movements. Land subsidence induced by aquifer system compaction is always associated with groundwater level drawdown and compressible layer. Therefore, it is important to analyze these two elements to understand the land subsidence mechanism. A number of researchers proposed different approaches to study this problem. Po-Lung et al. (2015) proposed an integrated subsidence model to analyze the soil compaction in multi-layer aquifer system due to groundwater abstraction. Analytical solution was used for simulation of flow and land subsidence was calculated based on the first consolidation theory. The integrated subsidence model has been applied to Yuanchang, Taiwan to investigate the effect of pumping on compaction of three-layer unconfined aquifer. The study revealed that a significant compaction occurred near the pumping well. Ye et al. (2015) proposed 3-D numerical model to simulate groundwater flow and multi-layer aquifer compaction in Shanghai. 3-D numerical model was also used to predict land subsidence. The results showed that increasing land subsidence has increased with increasing pumping.

Shen and Xu (2011) presented a numerical analysis to different scenarios of groundwater pumping to simulate and predict land subsidence in Shanghi. The numerical model incorporates 1-D consolidation into a 3-D seepage model of groundwater flow. The prediction of the future land subsidence is conducted via considering the variation of groundwater volume, pumping layer, and pumping region through reallocation of pumping wells. The study showed that the model simulates the variation of the coefficient of volumetric compressibility and hydraulic conductivity with the consolidation process. The calculated value of land subsidence using the model simulates the measured value fairly well. Gangul (2011) proposed an analytical model to simulate land subsidence in Singur Block, West Bengal, India. The study showed that the rate of land subsidence is directly controlled by the groundwater table drawdown, the saturated thickness of aquifer and the aquifer hydrogeological characteristics. Shen et al. (2004) proposed 3-D finite element model to calculate the land subsidence due to deep-ground water extraction. The study showed that high-pumping rates from deep sediment aquifers causes large areas effected by land subsidence.

In this study, MODFLOW is used to simulate groundwater flow and analytical model is used to evaluate the soil compaction in multi-layer aquifer considering different scenarios of abstraction and aquifer properties. Relationships between land subsidence and abstraction rate, hydraulic conductivity and specific storage have been developed to predict the future land subsidence in multi-layer aquifer.

2 METHOD AND MATERIALS

The current study includes integration of numerical and analytical solution to investigate the impact of increasing abstraction rates on land subsidence. Groundwater flow is simulated using MODFLOW then analytical solution is used to determine the land subsidence related to change in groundwater levels. The integrated models are applied to a case study to assess different scenarios of abstraction rates and aquifer properties.

2.1 Area description and flow domain

In this study a hypothetical case study is used to investigate the effect of increasing abstraction rates and changing aquifer properties on land subsidence. The case study domain is square of 2000 m length, 2000m width and 100 m depth. Figure 1 presents typical cross section and plan for the case study. Two rivers were allocated at right and left sides. Also, a number of 16 wells were installed at equal distance of 500 m in two directions.

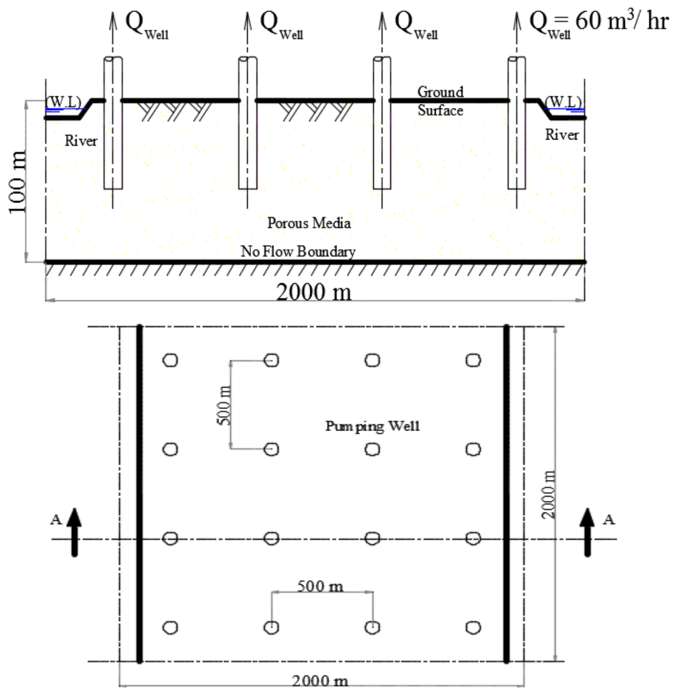


Figure 1. Plan and vertical cross section of the hypothetical case study

2.2 Numerical solution of groundwater flow

MODFLOW is used to simulate groundwater flow in multi-layer unconfined aquifer due to changing abstraction rate. The governing equation of groundwater flow is defined as following (McDonald and Harbaugh, 1988)

$$\frac{\partial}{\partial t}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)+W=S_s\frac{\partial h}{\partial t} \qquad (1)$$

Where; K_{xx}, K_{yy}, and K_{zz} are values of porous media hydraulic conductivity along the x, y, and z coordinate axes (LT^{-1}), h is the potentiometric head (L), W is volumetric flux per unit volume representing sources and/or sink of water in (T^{-1}), S_S is specific storage (L^{-1}), and t is time (T).

2.2.1 Boundary Conditions

Two rivers were assigned at the two boundaries with stage level from (97.50) to (98.00) and bed level from (92.50) to (93.00). Also, the annual recharge set equals to 320 mm/year.

2.2.2 Hydraulic Parameters

The hydraulic parameters of the study area were assigned based on the previous studies and mathematical calculations for similar cases (e.g. Abd-Elhamid et al. (2018)). The model was carried out for homogenous unconfined aquifer with 40 and 4 m/day horizontal and vertical hydraulic conductivities respectively. Also, the aquifer effective and total porosity is 20 and 30% respectively while the specific storage (S_s) is $4x10^{-4}$ m^{-1}.

2.2.3 Model calibration

Calibration is the process showing the different between calculated head by the model and observed or analytically calculated. The flow model is calibrated with results of one directional flow in unconfined aquifer based on Dupuit assumptions, Equation (2), Abd-Elhamid et al. (2018). The equation is used to calculate groundwater level between two parallel rivers shown in Figure 1.

$$\mathrm{h}^2 = {h_1}^2 + \frac{({h_1}^2-{h_2}^2)}{L}\,x + \frac{w}{K}(L-x)x \qquad (2)$$

Where: h is the groundwater elevation (L) between the two rivers, h_1 is the elevation of the river on the right (L), h_2 is the elevation of the river on the left (L), w is recharge rate (LT^{-1}), K is hydraulic conductivity (LT^{-1}), and x is the distance along the aquifer between two rivers (L). Figure (2) shows results of calibration and head contours in the aquifer. The model results are fairly well with the analytical solution.

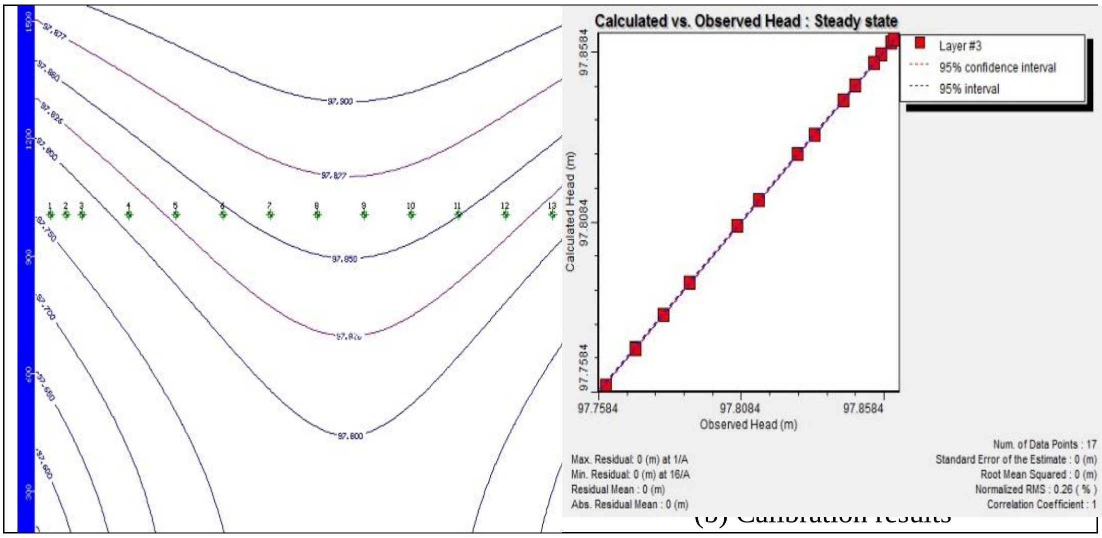


Figure 2. Head contour and model calibration results

2.3 Analytical Solution for Soil Deformation

Analytical solution is developed for the evaluation of compaction in multi-layer-aquifer due to changing groundwater levels. This solution is based on Terzaghi (1943) for one dimensional consolidation theory. This theory showed that decreasing pore water pressure (P) and effective stress (σ_e) was increased by the same value and the total stress (σ_t) remained constant with time as following:

$$\Delta\sigma e = -\Delta P = -\gamma_w \Delta h = \gamma_w \Delta s \quad (3)$$

The relation between effective stress and strain controls soil deformation behavior was expressed by Das (2006) as following:

$$\Delta\varepsilon = \alpha\, \Delta\sigma e = \alpha\, \gamma_w \Delta s \quad (4)$$

Also, the compaction of single soil layer can be determined based on change in effective stress and groundwater level as expressed by Terzaghi and Peck (1948) as following:

$$\delta_i(t) = \alpha\, \gamma_w \Delta s_i(t) b_i = \frac{S_{si}}{\gamma_w} \gamma_w \Delta s_i(t) b_i = S_{si} \Delta s_i(t)\, b_i \quad (5)$$

Therefore, land subsidence may be determined by accumulating compaction of soil layers expressed by Gambolati and Freeze (1973) as following:

$$\delta(t) = \sum_{i=1}^{n} \delta_i(t) = \sum_{i=1}^{n} S_{si}\ \Delta s_i(t) b_i \quad (6)$$

Where; σ_e is the effective stress, P is pore water pressure, γ_w is the unit weight of water, Δh is change in hydraulic head, Δs is drawdown of groundwater level, α is the compressibility of a porous medium, $\delta_i(t)$ is the compaction of single soil layer at any time S_{Si} : is the specific storage, and b_i is the thickness of soil layer.

3 RESULTS AND DISCUSSION

The integrated model is applied to the case study, Equation (1) is used to determine the groundwater levels and Equation (6) is used to determine the land subsidence in the aquifer. The effect of changing abstraction rates on land subsidence is investigated using different scenarios. Also, effect of changing abstraction rates on aquifer properties is also investigated including decreasing specific storage (Ss), hydraulic conductivity (k) and porosity (n). Different scenarios (15) for 3 main cases of increasing pumping rate, hydraulic conductivity and specific storage are used to investigate land subsidence in the aquifer. Table.1 presents the values of these scenarios and the results are shown in Figure 3 and illustrated below.

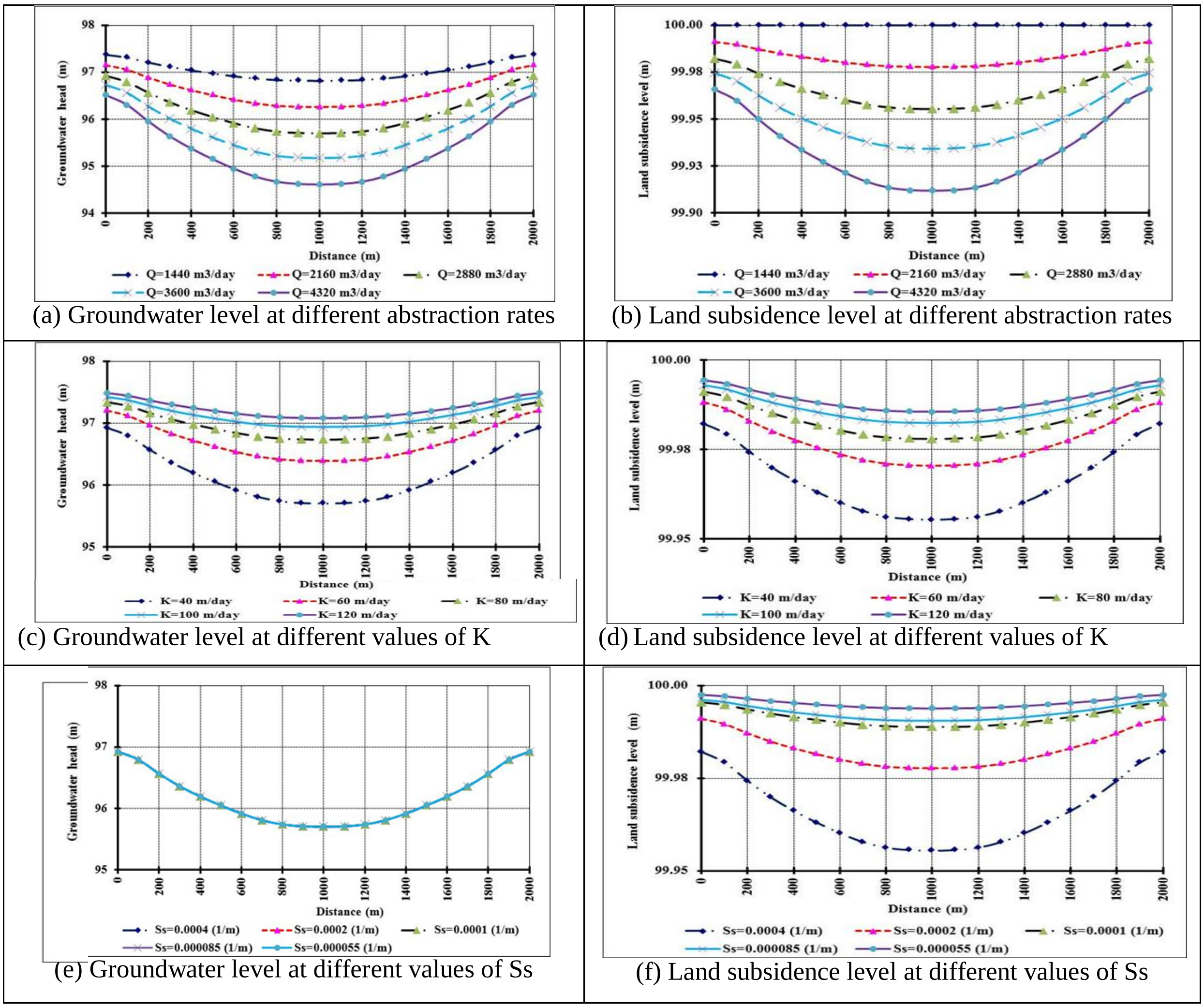
Table 1. Different proposed scenarios for pumping rates and aquifer parameters

Scenario	**Case 1** Pumping rate (Q) (m^3/hr/well)	**Case 3** Hydraulic conductivity (m/day)	**Case 2** Specific storage (1/m)
1	60	40	$4*10^{-4}$
2	90	40	$4*10^{-4}$
3	120	40	$4*10^{-4}$
4	150	40	$4*10^{-4}$
5	180	40	$4*10^{-4}$
6	120	40	$4*10^{-4}$
7	120	60	$4*10^{-4}$
8	120	80	$4*10^{-4}$
9	120	100	$4*10^{-4}$
10	120	120	$4*10^{-4}$
11	120	40	$4*10^{-4}$
12	120	40	$2*10^{-4}$
13	120	40	$1*10^{-5}$
14	120	40	$8.5*10^{-5}$
15	120	40	$5.5*10^{-5}$

The first case (scenarios 1 to 5) investigated the impact of increasing abstraction rate on land subsidence where the pumping rates has increased from 60 m^3/hr/well at the base case to 90, 120, 150 and 180 m^3/hr/well, while the aquifer properties are kept constant Ss equals to $4*10^{-4}$ m^{-1}, k equals to 40 m/day and n equals to 30%. Figures 3a and b shows the results of changing the abstraction rate on groundwater head and land subsidence at section (A-A). The results showed that increasing abstraction rates led to increase the drawdown and consequently the land subsidence has increased. As shown in Figure 3a and b, the highest values of drawdown and land subsidence occurred in the middle of the cross section due to increasing pumping rate and decreasing recharge from the rivers.

The second case (scenarios 6-10) assessed the impact of changing hydraulic conductivity (K) on land subsidence. The hydraulic conductivities are changed from 40 at the base case to 60, 80, 100 and 120 m/day as presented in in Tabel.1, while the pumping rate is kept constant 120 m^3/hr/well and the specific storage equals to $4*10^{-4}$ m^{-1}. Figures 3c and d presents the drawdown and land subsidence at different values of hydraulic conductivity at section (A-A). The figure shows that decreasing hydraulic conductivity due to change in abstraction rate has increased the drawdown and land subsidence.

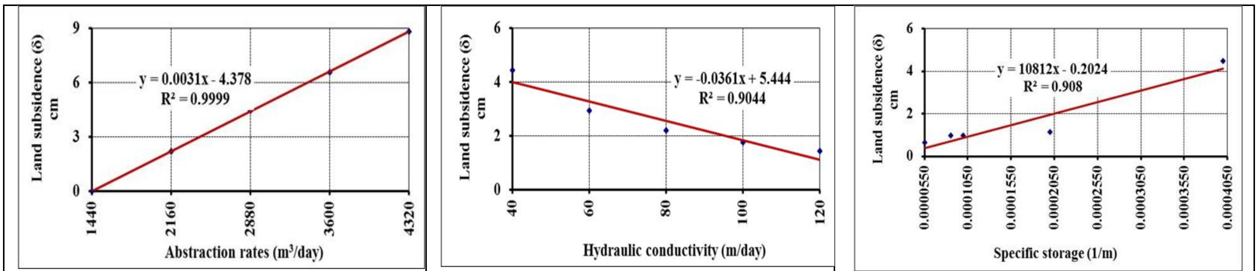
In the third case (scenarios 11-15) the effect of changing specific storage (Ss) on land subsidence is investigated. The specific storage is changed from $4*10^{-4}$ at the base case to $2*10^{-4}$, $1*10^{-5}$, $8.5*10^{-5}$ and $5.5*10^{-5}$ m^{-1} as presented in Tabel.1. The others values of pumping rates were kept 120 m^3/hr/well and hydraulic conductivity is 40m/day. The results showed that the drawdown hasn't affected by changing the specific storage as shown in Figures 3e but land subsidence has increased with decreasing specific storage as shown in Figures 3f.



(a) Groundwater level at different abstraction rates
(b) Land subsidence level at different abstraction rates
(c) Groundwater level at different values of K
(d) Land subsidence level at different values of K
(e) Groundwater level at different values of Ss
(f) Land subsidence level at different values of Ss

Figure 3. Results of groundwater level and land subsidence level for different scenarios

Increasing abstract rates led to increase drawdown and land subsidence which on turn affected the aquifer properties such as hydraulic conductivity, specific storage and porosity. Relationship between abstraction rate and land subsidence is presented in Figures 4a. The figure shows that increasing abstraction rate has increased land subsidence (δ). The figure provides a relationship that can be used to predict land subsidence at different abstraction rates. Figure 4b provides a relationship between hydraulic conductivity and land subsidence that also can be used to determine the land subsidence at any values of (K). Relationship between specific storage and land subsidence is presented in Figure 4c. The figure shows that decreasing specific storage has increased the land subsidence. The developed relationship can be used to determine land subsidence at different values of (Ss).



(a) Relationship between (δ) and Q
(b) Relationship between (δ) and K
(c) Relationship between (δ) and Ss

Figure 4. Results of the model for different values of specific storage (Ss)

4 SUMMARY AND CONCULSION

Land subsidence is a worldwide phenomenon, which accompanied with high pumping rates from groundwater aquifers. To assess the impact of changing groundwater levels and aquifer parameters including hydraulic conductivity and specific storage on land subsidence, MODFLOW is applied to a hypothetical case study to simulate groundwater flow. Analytical solution based on Terzaghi theory is applied to calculate the compaction of multi- aquifer system. The effect of changing pumping rates, specific storage (Ss) and hydraulic conductivity (K) on the land subsidence were simulated using different scenarios. The study showed that the increasing pumping rates has increase land subsidence. However, changing aquifer properties has different effects where decreasing the hydraulic conductivity increased both drawdown and land subsidence. But decreasing the specific storage has no effect on drawdown while increased land subsidence. But changing porosity has no effect on both drawdown and land subsidence. Relationships between land subsidence with abstraction rate, hydraulic conductivity and land subsidence have been developed that can be used to predict land subsidence with future changes in Q, K and Ss. Finally, to achieve a proper management of land subsidence, pumping rates and aquifer recharge should be adequately managed.

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