Assessment of soil subsidence due to long-term dewatering, Esna city, Egypt
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ABSTRACT
In Egypt, most of the residential areas lay on cohesive soil (clay) in the Nile valley and Delta and comprises of extensive irrigation network. Several regulators and barrages are located on the irrigation network. One of the sides effects of these regulators is the rising of water levels in the upstream causing the groundwater levels rising in the residential areas. The dewatering process becomes urgent in such areas to prevent the buildings from deterioration. Dewatering process causes an increase in effective stress and consolidation settlement. Esna city was selected to be the area of interest. This area has suffered from groundwater rising since the construction of the new Esna barrage in 1995 and due to the high surface water levels of some irrigation canals such as Ramady canal. The objective of this research is to assess the impact of different operating scenarios on soil subsidence and groundwater, and reaching the optimum scenario. Two maps were interpolated for the expected subsidence and desirable water levels from the most suitable scenario.

Introduction
Problem identification
Consolidation settlement is one of the most effective settlements that threaten the residential areas in Egypt. Most of residential areas in Egypt are located in Nile valley and delta because of surface water availability from the River Nile and its branches. The topsoil of these areas is cohesive soil. However, compressible soils are vulnerable to subsidence (Minderhoud et al., 2017). This area is about 5% of Egypt area (Brikowski, Smith, Shei, & Shrestha, 2004) and contains 97% of Egypt population. Many regulators were constructed upon River Nile branches and the main canals (Abdel-Dayem, Abdel-Gawad, & Fahmy, 2007). These regulators raise the water level in the upstream, causing the water table to rise in the residential area due to the hydraulic continuity between surface water and groundwater (Dawoud, El Arabi, Khater, & van Wonderen, 2006). However, the rise of water in residential areas threatens the buildings foundation and other infrastructure such as; sewage network, water drinking networks, light poles, and others. Therefore, it was essential to design a suitable dewatering system to lower the groundwater levels. Moreover, the design of the dewatering system has to consider the effect on soil subsidence.

Esna city was selected to be the case study in current research. It is located in upper Egypt (Qena governorate 150 km north Aswan city). Two barrages are located on the River Nile opposite to Esna city. The old one which is not currently working and was constructed in 1908. While the new one was constructed in 1995 and located 1150 m to North of the old one (Abu-Zeid, 1995). The residential area in Esna city is surrounded by a dense irrigation network from all directions (Monem, Faid, Ismail, & Schöniger, 2014). Esna city is bounded by the River Nile from the East, Asfon canal from the North, Maksar canal from the South and Ramady canal from the West.

One of the significant issues that threaten the residential area is the absence of the sewage network, while the drinking water network covers most of that area. Septic tanks are used to get rid of the sewage water in the city (Ghanem, Zaghoul, & El-Ayouti, 2011). Therefore, the residential area is surrounded by irrigation network, along with fluctuated water levels and has no sewage network. This leads to rise of the groundwater levels up to the street’s levels in several locations. Moreover, the groundwater is also rising inside the buildings (El-Fakhrany & Fekry, 2014). Therefore, the lowering of groundwater levels is an urgent and essential action.

A previous study of hydrogeological environment was conducted by (RIGW, 2010) to decrease the groundwater levels in the area. The dewatering well field technique was implemented. It consists of 20 pumping wells and allocated on five lines, covering the suffering residential area of water logging area.

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research covers such point using the new developed code (SUB-WT) by (USGS) that work as an additional compatible package for Modflow (as mentioned in paragraph 1.2)

**A computer program (SUB-WT)**

A computer program (SUB-WT) was developed by (USGS) to simulate vertical compaction of the soil in models of regional groundwater flow (Leake & Galloway, 2007). The program simulates groundwater storage changes and compaction in discontinuous interbeds or in extensive confining units, accounting for stress-dependent changes in storage properties. Compaction refers to the change in vertical thickness that accompanies changing stresses on the aquifer system. All aquifer systems undergo some degree of deformation in response to changes in stress. The seasonal cycle of recharge and discharge from unconsolidated heterogeneous aquifer systems typically causes measurable elastic (recoverable) compaction (Heywood, 1995; Poland & Ireland, 1984; Riley, 1969) and commensurate uplift and subsidence (millimeters to centimeters) of the land surface (Amelung et al., 1999; Bawden, Thatcher, Stein, Hudnut, & Peltzer, 2001; Hoffmann, Zebker, Galloway, & Amelung, 2001). Removing water from storage in the fine-grained silts and clays interbedded in the aquifer system causes these highly compressible sediments to compact, resulting in land subsidence. Fine-grained interbeds and confining units within or adjacent to unconsolidated aquifers that undergo head changes related to the development of the groundwater resource are particularly susceptible to compaction. As groundwater is drained to the coarser-grained sediments that constitute the aquifers, compaction can occur elastically (recoverable) or in-elastically (non-recoverable) causing permanent subsidence, depending on the stress history of these interbeds and confining units.

**Approach**

- Collection and compilation of previous studies on area of study;
- An additional fieldwork (measurements for groundwater, and subsurface water levels, drilling boreholes for soil);
- Laboratory analyses for soil sample (Sieve and Hydrometer Analysis, Atterberg Limits, Unconfined Compression Test and Consolidation);
- Surveying for ground level using the (DGPS) which is an advanced tool in measuring the topography using satellites system;
- A numerical model for Esna city was simulated and calibrated by using Modflow code through the GMS interface. The final calibration results were used as initial condition for testing five operation scenarios for dewatering well field. The additional package (SUB-WT) is merged with (GMS) model to estimate the resulted subsidence after testing the different operating scenarios, the threatened areas from water-rising and soil subsidence are identified; and
- Determine the most vulnerable zones that are threatened by differential settlement.

**Physical and hydrogeological settings**

**Location and geomorphology**

Esna city is located in upper Egypt. It extends from 25°16'49.24"N to 25°18'29.57"N and from 32°32'43.22"E to 32°33'42.80"E (Figure 1). The geographical location of Esna city plays an essential role in forming the geomorphological units in the area. Esna city lies on the flooded plain of the River Nile which is bounded by the limestone plateau and separated by some sandy hills and new agricultural land. The geomorphological units for the study area are Young alluvial plains, Old alluvial plains and Calcareous Structural Plateau.

In the study area, the lithological sequence contains sediment formation related to new, immediate and old ages. Some of these formations are above the ground surface, others are below the surface layers. While Some of such formations are found in deep layers. The most important hydrogeological formation is the quaternary formation which are Pliocene sedimentation ages, Pleistocene sedimentation ages, and Holocene sedimentation ages.

**Hydrogeological settings**

The main important aquifer in the study area is the Quaternary Aquifer (Figure 2) which extents along the River Nile from Aswan to Cairo (RIGW, 1994). The quaternary aquifer is limited in the east and west by the elevated limestone plateau which is located in the eastern and western desert at both sides of the River Nile. The hydrogeological maps indicate that the component layers for the Quaternary aquifer are; the agriculture surface soil layer of clay with average thickness 1.5 m, the top unit of clay and silt aquitard with average thickness 15 m which overlays the sand and gravel aquifer layer with 250-m thickness. The aquifer is confined by the base of aquifer Pliocene Clay. The quaternary aquifer is recharged with about 0.002 mm/day through infiltration from: excess irrigation water from river, canals, and drains which are covering almost the area; sewage networks or septic tanks; and groundwater movement from other aquifers (e.g.: Nubian aquifer). The main flow direction in the study area is from South West to North East with groundwater levels ranges between (78.00) and (79.00), with average equals to 78.50 AMSL.
Figure 1. The location study area.

Figure 2. Hydrogeological map for the study area.
Soil properties and data collection

**Filed works**

In order to evaluate the impacts of the different operating scenarios for pumping wells dewatering method on soil subsidence, it was important to identify the geotechnical properties of the soil in study area. The required soil properties data to be used through the SUB-WT code are: thickness of interbed in the layer; compression index \((C_c)\); recompression index \((C_r)\); void ratio \((e)\); geostatic stress above layer one and initial compaction \((p_c)\). Data were collected from a number of 30 boreholes drilled previously by RIGW. The collected data from the 30 boreholes were illustrated at the soil profile for the study area, to be used as data entry in the modeling process. Also, during the research work, a number of additional four boreholes were drilled in different locations at the city to determine the geotechnical properties of soil in the study area. The depth of the four boreholes is 12 m. The soil samples were collected for every 1 m from the soil column. Samples were isolated and shipped to the lab to conduct the required laboratory tests and calculate the geotechnical properties of these samples.

**Laboratory tests**

Most of the collected samples were cohesive soil (clay). The main objective of the laboratory tests is to understand the nature of soil properties in the study area and obtain accurate values for the effective variables in soil subsidence. The conducted tests were; a) Sieve and Hydrometer Analysis, b) Atterberg Limits, c) Unconfined Compression Test and d) Consolidation Test. From consolidation test, the required factor value for SUB-WT package \(C_c, C_r, e, \phi, p_c\) are calculated and listed in (Table 1). A sensitivity analysis was conducted to identify the effect of such soil factors on soil subsidence for determining the most sensitive factors on subsidence process.

**Groundwater flow and soil models**

**Simulation and calibration of groundwater flow model (GMS)**

In order to understand the nature of groundwater movements, levels, and the hydraulic connection between different water sources, a numerical model was applied for the study area. The input data were collected from previous studies and the field measurements during the current research work. “Modflow” code through GMS interface version 10.0.8. was used in the simulation and calibration.

**Model description and boundary conditions**

The modeled area is 3481 m in “X” direction * 4339 m in “Y” direction (Figure 3). The model was discretized into 140 columns * 174 rows and divided into four layers in the vertical direction. The model boundary conditions are defined as follows: The East and north boundary were defined as the constant head. However, the West and South boundary are defined as no-flow boundary.

**Numerical model input**

The required input data are: (topography; aquifer geometry, its extension, and hydraulic parameters; the initial groundwater and subsurface levels ground surface levels; surface water levels and its hydraulic parameters; the net recharge; and the soil stratigraphy).

The ground surface levels were generated from previous studies and it was verified by using the Differential Global Position System (DGPS). The ground surface levels in the study area range from 79.3 to 82 m (AMSL). Groundwater levels were collected from implemented shallow and deep observation wells by (RIGW, 2010). The monitoring process covered four months (November 2009 to February 2010). The hydraulic connection between the upper and lower layer were studied from deep and shallow wells in the same locations (Figure 4). The chart indicates that there is a strong matching between both groundwater and subsurface water levels. Measured contour map for the groundwater levels was drawn (Figure 5) to be used as an initial condition for the calibration process and help to identify the boundary condition of the model area.

Surface water levels data were collected for the different surface water networks in the study area such as: The River Nile, Asfon Canal, Ramady canal, and Maksar canal as shown in (Figure 6). The figure indicates the simulated surface water system and their levels. It was observed that the high surface water levels as a source line in the west and south boundaries of the residential area.

The calculated hydraulic parameters of the aquifer based on 12 aquifer tests that were conducted by RIGW (2010). The calculated storativity value is \(5 \times 10^{-5}\). The specific storage value is 0.005 for third and fourth layer while, for first and second layer the specific storage is obtained from literature with the value of 0.0025.

| BH   | DEPTH | Cc  | Cr  | e    | p_c kg/cm² |
|------|-------|-----|-----|------|------------|
| BH_1 | (3–4) | 0.406 | 0.0362 | 0.375 | 1.8        |
|      | (8–9) | 0.16  | 0.0107 | 0.56  | 0.75       |
| BH_2 | (3–4) | 0.32  | 0.023  | 0.32  | 1.5        |
|      | (3–4) | 0.33  | 0.024  | 0.65  | 1.6        |
| BH_3 | (3–4) | 0.34  | 0.056  | 0.23  | 2.0        |
|      | (8–9) | 0.073 | 0.0073 | 0.28  | 1.2        |
Figure 3. Grid discretization and model boundary.

Figure 4. The correlation between shallow and deep groundwater.
The net recharge rate was estimated to be 0.002213 m/day from septic tanks due to unavailability of sewage network. While the net recharge from the agriculture area at the east fringes of the study area was estimated with values ranging from 0.001 to 0.0005 m/day.

The soil stratigraphy in the study area was investigated by RIGW through 30 boreholes covering Esna city. Rockworks software was used to interpolate the results of borehole data to develop a conceptual 3D model for the stratigraphy of the study area. The analysis was conducted by the software classifying the soil profile into four different layers: The first layer is about 3 m thickness and consists of fill with some interbeds of clay. The second layer is 7 m thickness and consists of clay with very low hydraulic conductivity however, this layer is intercalated by some lenses of sand which increases hydraulic conductivity of this layer. The third layer consists mainly from sand mixed with silt or clay with average depth 3 m as the top part of the aquifer; and the last layer consists of sand and gravel which forms the aquifer formation with average depth 250 m.

Numerical model calibration

The model was simulated and calibrated against the measured groundwater levels. To minimize the error between the calculated and the measured levels. Several trials were done by changing the hydraulic conductivity, the recharge and conductance values were executed. (Figure 8) shows the final calibration results verses the measured groundwater levels chart. The figure indicates the great agreement between the calibrated and measured groundwater levels. (Figure 9) shows the most threatened locations suffering from high groundwater levels (waterlogged area) in the study area.
Subsidence calculation model

Digital models of groundwater flow are widely used to study the response of aquifer systems from pumping stress. A new computer program (SUB-WT) was developed by (USGS) to simulate the vertical compaction in models of groundwater flow (Leake & Galloway, 2007). The program simulates groundwater storage changes and compaction in discontinuous interbeds or in extensive confining layers, accounting for stress-dependent changes in storage properties. This program especially, was developed to be a compatible package for MODFLOW, the U.S. Geological Survey modular finite-difference groundwater flow model. Several features of the program make it useful for application in shallow, unconfined flow systems. Geostatic stress can be treated as a function of water-table elevation, and compaction is a function of computed changes in effective stress at the bottom of a model layer. Thickness of compressible sediments in an unconfined model layer can vary in proportion to saturated thickness.

Geotechnical soil subsidence equations

The compaction occurring due to change of effective stress is calculated using Terzaghi’s theory (Terzaghi, 1925). According to Terzaghi’s equation, the increase in subsidence is linked to an intergranular increase in effective stresses.

According to Terzaghi’s equation

\[ \sigma'_{ij} = \sigma_{ij} - \delta_{ij} u \]

Where \( \sigma'_{ij} \) is a component of the effective-stress tensor, \( \sigma_{ij} \) is a component of the geostatic (total) stress tensor, \( \delta_{ij} \) is the Kronecker delta function, and \( u \) is the fluid pore pressure or hydrostatic stress.

Figure 6. Surface water levels for irrigation system in study area.
The general expression for compaction or expansion of sediments, $\Delta b$, between times $t_{n-1}$ and $t_n$ as follows:

$$\Delta b = \frac{0.434 b_0}{(1 + e_0)\sigma} \left[ C_n \left( \sigma_n - \sigma'_{c,n-1} \right) + C_r \left( \sigma'_{c,n-1} - \sigma_n \right) \right]$$

$$C_n = \begin{cases} C_r, & \sigma_n > \sigma'_{c,n-1} \\ C_r, & \sigma_n \leq \sigma'_{c,n-1} \end{cases}$$

(4–1)

where $\sigma'_{n-1}$ and $\sigma'_n$ are effective-stress values at times $t_{n-1}$ and $t_n$ respectively, and $\sigma'_{c,n-1}$ is the pre-consolidation-stress value at the time $t_{n-1}$. Note that the relation of $\sigma'_n$ to $\sigma'_{c,n-1}$ is used to determine whether the value of $C_n$ is $C_r$ or $C_c$. The expression gives correct results for overly consolidated sediments, for normally consolidated sediments, and for sediments in the transition from over-consolidation to normal consolidation.

**Operating scenarios for dewatering**

This paragraph presents the implementation of five operating aquifer scenarios on the existing dewatering well field (20 wells were constructed in the year 2009–2010 by RIGW) under the area of interest for dewatering. Those scenarios mainly, depend on the final results of the calibration of groundwater flow model as an initial condition. To assess their impacts as dewatering system on the soil subsidence, maintaining the groundwater levels at the desirable levels and minimizing the resulted soil subsidence.

The selected existing dewatering system that was implemented through well field consists of 20
pumping wells which are allocated in five lines to transfer the extracted water to Ramady canals (Figure 10). Two proposed schemes were suggested by (RIGW, 2010) for operating the well field; 30 and 40 $m^3$/hour, respectively. In this research, those two schemes were tested through the current research. In

Figure 9. The threatened locations from groundwater model in study area.

Figure 10. Locations of pumping wells and pipe line.
addition, another three-operating scenarios for the same existing well field were proposed and studied in order to find an appropriate scenario that satisfies the desired drawdown in short time and decrease the long-term cost. And also, to be applicable for rehabilitation and maintenance, as follows:

- **The first operation scheme (W-A)**: is to operate all well field of dewatering at 30 m³/hour continuously.
- **The second operation scheme (W-B)**: is to operate all well field of dewatering at 40 m³/hour continuously.
- **The third operating scheme (W-C)**: is to operate half of the wells at 80 m³/hour, alternatively in staggered pattern.
- **The fourth operating scheme (W-D)**: is to operate the line of pumping wells adjacent to the Ramady and Maksar canal with extraction rate equals to 60 m³/hour while operating the rest of the wells at 30 m³/hour.
- **The fifth operating scenario (W-E)**: one day on and off operating schedule plan for all pumping wells field. For the first 300 days, the extraction rate will be 100 m³/hour, and decrease to 75 m³/hour for the next 200 days. And finally, the extraction rate was kept at 30 m³/hour till the end of the run.

All of such scenarios were tested using the developed calibrated model and integrating with the additional package (SUB-WT) to calculate and check the soil subsidence for each of them.

The results of operating scenarios

By comparing the first four tested scenarios (Figure 11), it was clear that the minimum groundwater lowering obtained from the first scenario (W-A) with 2.38 m drawdown from the starting groundwater level with minimum subsidence value equals 64 mm. While the maximum drawdown was obtained from the scenario (W-C) with 3.44 m drawdown from the starting groundwater level with maximum subsidence value equals to 78 mm. It is also, notes that the scenarios (W_B, W_C, and W_D) are nearly similar in their results.

Figure 12 shows that, the required groundwater level was achieved through (W_E) after 350 days from starting the extraction. The draw-down increased to 1.46 m after 867 days then it was raised again to 1.10 m at the end of the stress period. The relevant extracted volume of water in this scenario is 9173 m³/day which is significantly smaller to the other tested scenarios. (Figure 13) indicates the expected groundwater level contour map under the same scenario (W_E). (Table 2) summarizes all the tested five operating scenarios with the expected maximum drawdown, time to reach steady state condition, total-extracted volume of water, and resulted subsidence. According to the last scenario, it was also obtained that the expected maximum subsidence is 63 mm which is the least value of soil subsidence than those of the other scenarios. (Figure 14) shows the resulted ground surface subsidence and highlight the most threatened area by differential settlement.

Conclusions and recommendations

Conclusions

From the analyses of the prevailing hydrogeological condition, and soil profiles under study area. They indicate that there is spatial top soil diversity in the vertical direction and seasonal groundwater level fluctuations which have a big effect of the accuracy of soil subsidence.

![Figure 11. Drawdown with time for all tested dewatering scenarios.](image-url)
**Figure 12.** Drawdown with time for optimum scenario and the two main scenarios.

**Figure 13.** Contour map for groundwater levels of the (W_E) scenario.
In this research, the (SUB-WT) package that developed by (USGS) was merged with the groundwater flow model using (GMS) interface as an additional package and compatible with it. Taking in consideration, the diversity of the topsoil in the vertical direction and effect of groundwater fluctuation on soil subsidence. Through this research, these tools were used to

Table 2. Comparison between tested scenarios outputs.

| Sc. Name | Sc. Description | Max Drawdown (m) | Time to reach steady state (days) | Daily extraction volume (m³/d) | Max subsidence value (mm) |
|----------|-----------------|------------------|----------------------------------|-----------------------------|--------------------------|
| W-A      | 30m³/h continuously all wells | 2.38 | 2400 1000 | 14400 | 64 |
| W-B      | 30m³/h continuously all wells | 3.29 | 1900 1000 | 19200 | 75 |
| W-C      | One day Alternative Extraction rate of 80 m³/hour | 3.44 | 1800 1250 | 19920 | 78 |
| W-D      | Continuous variable pumping rate of 30 and 60 m³/hour(W_D) | 3.24 | 1800 1200 | 20160 | 76 |
| W-E      | One day on and off operating schedule | 1.46 | 350 100 | 9173 | 63 |

Figure 14. Contour map in millimeter shows the resulted subsidence and most threaten area according to gradual decreasing pumping rates (W_E).
enhance and refine the soil subsidence calculation from dewatering system under the proposed scenarios.

- The analysis of field measurements indicates that there are no significant differences between subsurface and groundwater levels. This means that there is a mutual influence between the surface water system and groundwater. This causes a remarkable increase in the groundwater levels which in turn causing the appearance of water above the ground surface (waterlogging phenomena) at various location of the residential area.
- Number of five dewatering scenarios were tested (W_A, W_B, W_C, W_D, and W_E). The first four scenarios achieved drawdown ranges between 2.38 and 3.44 m which is beyond the desired drawdown with rather big-extracted water volume. This leads to high-cost operation with long-time operation. This means such four scenarios are difficult to be applicable. While the final scenario (W-E) achieved the desired groundwater level (1.46) in short time (350 day), with low cost, and minimum effect on soil subsidence (63 mm).
- There are two interpolated maps (Figures 13 and 14) represents the output of the last scenario (W-E) for both models:
  - The first interpolated map (Figure 13) indicates that the expected groundwater levels after the dewatering pumping scenario with maximum lowering in groundwater level 1.46 m at center of the area. Moreover, there is a local significant change in the flow direction of the study area which acts as a sink area.
  - The second interpolated map (Figure 14) shows the areal distribution for the subsidence values covering the model area where the maximum value is occurred in the middle of it and decreased radially to the outer limits. Such map can help the decision maker to delineate and give the priority hazard area for dewatering.
- Updating both the groundwater flow and soil models for dewatering according to the hydrogeological changes (groundwater fluctuations, surface water projects, etc.) in the study area to monitor the change in the soil subsidence.
- Assess other dewatering techniques on groundwater levels and soil subsidence.
- More verification for the soil layers by implementing more advanced geophysical techniques to generate more detailed sections for the soil layers. And identifying the exact locations of filling, clay and sand material.
- It is very important for the implementing any operating scenarios for dewatering does not change the groundwater flow direction and water balance outside the dewatering area.
- It should be monitored the effect of dewatering system subrationally and regionally as well with time.

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References
Abdel-Dayem, S., Abdel-Gawad, S., & Fahmy, H. (2007). Drainage in Egypt: A story of determination, continuity, and success. *Irrigation and Drainage*, 56(S1), S101–S111.
Abu-Zeid, M. (1995). Major policies and programs for irrigation drainage and water resources development in Egypt. *Options Méditerranéennes, Sér. B*, (No. 9, pp. 33-49).
Amelung, F., Galloway, D. L., Bell, J. W., Zebker, H. A., & Lacziuk, R. J. (1999). Sensing the ups and downs of Las Vegas: InSAR reveals structural control of land subsidence and aquifer–system deformation. *Geology*, 27(6), 483–486.
Bawden, G. W., Thatcher, W., Stein, R. S., Hudnut, K. W., & Peltzer, G. (2001). Tectonic contraction across Los Angeles after removal of groundwater pumping effects. *Nature*, 412(6849), 812.
Brikowski, T. H., Smith, L. S., Shi, T. C., & Shrestha, S. D. (2004). Correlation of electrical resistivity and groundwater arsenic concentration, Nawalparasi, Nepal. *NepJOL*, 30, 99–106.
Dawoud, M. A., El Arabi, N. E., Khater, A. R., & van Wonders, J. (2006). Impact of rehabilitation of Assiut barrage, Nile River, on groundwater rise in urban areas. *Journal of African Earth Sciences*, 45(4–5), 395–407.
El-Fakhary, Z., & Fekry, A. (2014). Assessment of New Esna barrage impacts on groundwater and proposed measures. *WJ*, 28(1), 65–73.
Ghanem, H., Zaghloul, S., & El-Ayouti, S., 2011. Groundwater lowering in multi-layer aquifer systems: Case study of Esna city – Egypt. 64th Canadian Water Resources Association National Conference "Our Water – Our Life – The Most Valuable Resource", June 27 to 30, 2011, St. John’s NL CANADA.

Heywood, C. E., 1995. Piezometric-extensometric estimations of specific storage in the Albuquerque Basin, New Mexico. US Geological Survey Subsidence Interest Group Conference, Proceedings of the Technical Meeting, Las Vegas, Nevada, United States of America, Vol. 97, 21.

Hoffmann, J., Zebker, H. A., Galloway, D. L., & Amelung, F. (2001). Seasonal subsidence and rebound in Las Vegas Valley, Nevada, observed by synthetic aperture radar interferometry. Water Resources Research, 37(6), 1551–1566.

Leake, S. A., & Galloway, D. L. (2007). MODFLOW ground-water model-user guide to the subsidence and aquifer-system compaction package (SUB-WT) for water-table aquifers (No. 6-A23). Geological Survey (US).

Lu, Z., & Danskin, W. R. (2001). InSAR analysis of natural recharge to define structure of a ground-water basin, San Bernardino, California. Geophysical Research Letters, 28(13), 2661–2664.

Minderhoud, P. S. J., Erkens, G., Pham, V. H., Bui, V. T., Erban, L., Kooi, H., & Stouthamer, E. (2017). Impacts of 25 years of groundwater extraction on subsidence in the Mekong delta, Vietnam. Environmental Research Letters, 12(6), 064006.

Monem, M. A., Faid, A., Ismail, E., & Schöniger, M. (2014). Groundwater management in the Esna city, Upper Egypt: An application of remote sensing and numerical modeling. Natural Resources Journal, 5(12), 732.

Poland, J. F., & Ireland, R. L., 1984. Land subsidence in the Santa Clara Valley, California as of 1980 (No. 84-818). USGS RIGW, 1994: Hydrogeologic Map of Egypt, Scale 1: 100,000, Esna Research Institute for Groundwater, Egypt.

RIGW, 2010. Final Technical Report for Esna hydrogeological study. Egypt: Research Institute for Groundwater.

Riley, F. S. (1969). Analysis of borehole extensometer data from central California. Land Subsidence, 2, 423–431.

Terzaghi, K. (1925). Erdbaumechanik auf bodenphysikalischer Grundlage.