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AKİFER SİSTEMİNDE YERALTI SU SEVİYESİ DEĞİŞİMİNDEN KAYNAKLI ALANSAL OTURMALARIN HESAPLANMASI

CALCULATION OF LAND SUBSIDENCE DUE TO GROUNDWATER LEVEL CHANGE IN AQUIFER SYSTEM

Barış ÇAYLAK[1], Ali Hakan ÖREN[2], Elif Aysu BATKAN[3],
Mustafa Berker BAYIRTEPE[4], Alper ELÇİ[5], Carolina GUARDIOLA-ALBERT[6],
Guadalupe BRU[7], Pablo EZQUERRO[8], Roberto TOMÁS[9],
María Inés NAVARRO-HERNÁNDEZ[10]

ÖZET

Yeraltı su seviyesindeki düşmeler zemin oturmasına neden olur. Bu oturma, altyapı, bina ve diğer yapıların zarar görmesine yol açabilir. Yeraltı su seviyesindeki ani düşmeler, zemindeki oturmanın hızını artırabilir. Bu nedenle, yeraltı su seviyesi değişimleri inşaat ve yapı güvenliği açısından önemlidir. Bu çalışmanın amacı, zemindeki oturmaları tespit etmek için bir yöntem sunmaktadır. Manisa İli'nde, Alaşehir-Sarıgöl ilçelerini içine alan bir bölgede uydu tabanlı radar yöntemi InSAR (Interferometric Synthetic Aperture Radar) kullanılarak Ocak 2019 - Ağustos 2021 arasında önemli miktarda alansal oturma meydana geldiği belirlenmiştir. Bu oturmanın yeraltı su seviyesi değişimlerine bağlı olup olmadığını araştırmak için sonlu farklar yöntemini temel alan Modflow-2005 yeraltı su akış modeli ile bölgedeki yeraltı su seviyeleri zamansal ve mekânsal olarak hesaplanmıştır. Ayrıca, akiferin su tutma veya salma kapasitesini ifade eden depolama katsayısını belirlemek amacıyla gözlem kuyularındaki su seviyeleri ile InSAR yer değiştirmesi değerleri kullanılmıştır. Böylece depolama katsayısı ve yeraltı su seviyesi düşüşü parametreleri ile oturma hesaplanabilmiştir. InSAR ile tahmin edilen oturma değerleri ile karşılaştırıldığında hesaplanan oturmaların ortalama mutlak hata (MAE) değeri 2,4 cm/yıl olarak hesaplanmıştır. Bu yöntem, yeraltı su seviyelerinin değişimlerine bağlı olarak zeminde meydana gelen oturmaları yakşalık olarak belirleme imkanı sunmaktadır.
Anahtar Kelimeler: *InSAR, Gerilim-Gerinim eğrisi, Alansal oturma, Modflow, Gediz Nehir Havzası*

ABSTRACT

Groundwater level decrease can result in land subsidence, which may cause damaging impacts on infrastructure, buildings, and other structures. Additionally, a sudden decrease in groundwater levels can escalate the rate of subsidence, underscoring the importance of monitoring groundwater level fluctuations for the purposes of construction and building safety. The objective of this investigation is to propose a method for identifying subsidence. Using the satellite-based radar technique InSAR (Interferometric Synthetic

[1] Doktora Öğrencisi, Dokuz Eylül Üniversitesi Fen Bilimleri Enstitüsü, bariscaylak91@gmail.com
[2] Prof. Dr., Dokuz Eylül Üniversitesi İnşaat Mühendisliği, ali.oren@deu.edu.tr
[3] Doktora Öğrencisi, Dokuz Eylül Üniversitesi Fen Bilimleri Enstitüsü, aysubatkan@gmail.com
[4] Yüksek Lisans Öğrencisi, Dokuz Eylül Üniversitesi Fen Bilimleri Enstitüsü, berker_b@hotmail.com
[5] Prof. Dr., Dokuz Eylül Üniversitesi Çevre Mühendisliği, alper.elci@deu.edu.tr
[6] Dr., İspanya Jeoloji ve Madencilik Enstitüsü, c.guardiola@igme.es
[7] Dr., İspanya Jeoloji ve Madencilik Enstitüsü, g.bru@igme.es
[8] Dr., İspanya Jeoloji ve Madencilik Enstitüsü, p.ezquerro@igme.es
[9] Prof. Dr., Alicante Üniversitesi İnşaat Mühendisliği, roberto.tomas@ua.es
[10] Doktora Öğrencisi, Alicante Üniversitesi İnşaat Mühendisliği, mainnahe@ua.es

Aperture Radar) in an area which includes the districts of Alaşehir-Sarıgöl in Manisa Province, it was observed that a substantial amount of land subsidence occurred between January 2019 and August 2021. To determine if there is any connection between this subsidence and changes in groundwater levels, we computed groundwater levels in the area both temporally and spatially using the finite-difference method within the MODFLOW-2005 groundwater flow model. Furthermore, we determined the storage coefficient, which characterizes the ability of the aquifer to withhold or release water, by utilizing water levels in observation wells and InSAR displacement values. Thus, subsidence can be determined by considering the parameters of storage coefficient and decline in groundwater level. The mean absolute error (MAE) value of the calculated subsidence was found to be 2.4 cm/year when compared with the displacement values estimated by InSAR. This method presents an approximate way to assess land subsidence caused by changes in groundwater levels.
Keywords: *InSAR, Stress-Strain Curve, Land Subsidence, Modflow, Gediz River Basin*

1. INTRODUCTION

Land subsidence is an important phenomenon affecting the management and sustainability of groundwater resources. It results from the indirect displacement of groundwater due to gravitational effects and is influenced by several factors (van Dam et al., 2007). The importance of subsidence is multifaceted. Primarily, it affects the prudent utilization of natural water reservoirs. Changes in groundwater levels may have a direct impact on the quantity and quality of available water resources (Ostad-Ali-Askari & Shayannejad, 2021). Therefore, it is essential to have a precise understanding of subsidence to maintain the sustainable use of groundwater resources.

To ensure the safety and security of infra- and super-structures, a comprehensive comprehension of subsidence mechanisms is necessary. This is especially relevant in cases where these structures are located near water sources, as the consequences of subsidence can be significant. Ignoring subsidence in the design and construction of such structures can result in damage, cracks, and durability problems. This not only causes financial losses but also poses risks to human safety.

Land subsidence provides valuable insights into understanding the impacts of climate change which allows the forecasting of future circumstances (Dragoni & Sukhija, 2008). Changes in rainfall patterns and amounts caused by climate change can lead to alterations in groundwater levels and flow patterns. This information can assist in developing strategies to tackle climate change and improve water resource management. In conclusion, land subsidence plays a crucial role in sustainably managing groundwater resources, protecting infra- and super-structures, and understanding the effects of climate change. Therefore, precise monitoring, assessment, and management of subsidence are essential for conserving and ensuring sustainable water resource usage.

The storage coefficient, S, measures the capacity of an aquifer, typically a high-permeability layer, to store water. It is related to the aquifer's porosity, or void volume, and its storage capacity, i.e., the ability to hold and release water. Various experimental, numerical, and analytical techniques for measuring the storage coefficient are presented in the literature, including aquifer tests, tracking groundwater levels, groundwater modelling and geophysical techniques (e.g. Banton & Bangoy, 1996; Chen et al., 2018).

Apart from the storage coefficient, groundwater recharge stands out as another crucial parameter. It is the supply of water to the aquifer by means of precipitation and/or lateral flow from neighboring units. This parameter is influenced by factors such as precipitation, hydrogeological properties, groundwater depth, and human interventions. Groundwater recharge is typically assessed through data obtained from monitoring wells measuring groundwater levels. These wells usually are fitted with sensors that can measure water levels and detect changes over time. By examining this data, fluctuations in groundwater levels are analyzed and groundwater exchange rates are established.

The literature contains numerous investigations and studies related to the storage coefficients and groundwater change. These investigations cover a wide range of topics such as modeling the dynamics of groundwater flow and water resource management. Researchers use various methods, including field tests, and analytical solutions to determine storage coefficient (Bonì et al., 2020; Chen et al., 2016).

The aim of this study is to provide a methodology for the prediction of subsidence in Alaşehir-Sarıgöl, in Manisa Province, an area subjected to regional land subsidence. Groundwater flow was simulated using the finite-difference approach of MODFLOW-2005 (Harbaugh, 2005). One of the resulting outcomes of the model was the spatial and temporal distribution of groundwater levels. Additionally, InSAR (Interferometric Synthetic Aperture Radar), a remote sensing technique used to measure ground movements, was implemented to identify land subsidence between January 2019 and August 2021. The stress-strain relationship, which was derived from InSAR displacement data corresponding to groundwater levels in each observation well within the groundwater flow model, facilitated the computation of the storage coefficient. This coefficient expresses the soil's capacity to hold or release water per unit change in water level. Therefore, subsidence was evaluated using the storage coefficient and variables depicting the decrease in groundwater level.

2. METHOD

SAR images were acquired via the Sentinel-1 satellite. The Coherent Pixel Technique (CPT) process (Blanco-Sànchez et al., 2008) was utilized to acquire a time series of land subsidence, along with the annual spatial displacement value. Then a comparison was made between this spatial displacement distribution and the calculated settlement.

The settlement phenomenon relies on variations in stress, deformable soil thickness, and specific storage, as shown in Equation 1 (Navarro-Hernández et al., 2020). If these parameters are ascertainable, spatial displacement for the designated region can be computed.

$$\delta = D \cdot \Delta h \cdot S_{sk} = \Delta h \cdot S_k \quad (1)$$

where δ represents the displacement (in meters) of the deformable soil layer thickness (D), and Δh denotes the change in piezometric level. S_{sk} reflects the specific storage that represents the soil's deformability (in m^{-1}), and S_k is the deformable soil's storage coefficient (dimensionless) (Tomás et al., 2011). The S parameter in the equation represents the aquitard's storage coefficient, which also signifies the soil's capacity to deform. In a study by Tonkul et al. (2019), the digitized spatial storage coefficient distribution map was employed, created with well-test data from the alluvial plain.

S_k or S_{sk} denotes the aquitard's deformability and fluctuates with the stress state, acquiring a different value dependent on the piezometric level (H) and its position above or below the maximum recorded piezometric decline (H_p). Therefore, H_p is equivalent to the well-known pre-consolidation stress of soil used in geotechnical engineering, which represents the maximum effective stress experienced by the soil. This value distinguishes elastic, recoverable deformations from inelastic, unrecoverable deformations as shown in Equation 2.

$$S_k = \begin{cases} S_{ke} \; if \; H > H_p \\ S_{kv} \; if \; H < H_p \end{cases} \quad (2)$$

The S_{kv} coefficients for inelastic storage in the aquitard have been computed using piezometric time series data from nine different wells in Alaşehir-Sarıgöl region. Furthermore, InSAR-derived deformation data corresponding to these datasets are accessible. These datasets establish the basis for developing stress-strain curves that reveal the relationship between changes in piezometric levels and deformations within the aquitard. This methodology has been utilized by numerous researchers (Galloway & Hoffmann, 2007; Hoffmann, 2003; Tomás et al., 2006). The method involves determining the gradient of the stress-strain curve as shown in Equation 3.

$$S_k = \frac{\delta}{\Delta h} \quad (3)$$

The elastic storage coefficient (S_{ke}) has been computed as a percentage of the anelastic storage coefficient (S_{kv}). For this purpose, the ratio between the re-compression index (C_r) and the compression index (C_c), C_r/C_c, which are comparable to the S_{ke} and S_{kv} coefficients, has been considered. Consequently, the elastic storage coefficient was estimated by taking this ratio as 10% as an approach.

A numerical groundwater flow model with a subsidence calculation extension was set up to identify subsidence resulting from excessive exploitation of groundwater. Changes in groundwater levels over time were analyzed using this model that was originally calibrated with well observations. In this regard, drawdown values spanning the InSAR observation period could be applied to plot a stress-strain curve. The slope of the curve was used to calculate storage coefficients for each well. Data input as S_{kv}, S_{ke}, pre-consolidation head was required for MODFLOW's SUB package (Hoffman et al., 2003) to simulate aquifer system compaction and land subsidence. This was achieved by interpolating the storage coefficient values for each observation well. The resulting modeled subsidence values were compared with InSAR-derived subsidence values over a period.

3. RESULTS

Through the use of the advanced remote sensing technique InSAR, a thorough study was carried out to measure the complex compaction dynamics within the designated study area, particularly the Alaşehir sub-basin. InSAR is an incredibly valuable tool, enabling the identification of the intricate relationship between geological shifts and environmental factors. Figure 1(a) accurately depicts the results of this thorough analysis, illustrating the chronological progress of compaction dynamics. Covering the timespan between January 2019 and August 2021, the calculated yearly compaction figures effectively relate the developing topographic phenomenon. It is important to note that these assessments revealed instances of significant subsidence, with the most notable being a maximum magnitude of 15.0 cm/year. These findings also uncovered occurrences of uplift, up to 3.9 cm/year. The complex variations in the landscape's response highlight the intricate interplay of geological, hydrological, and anthropogenic forces that collectively influence the dynamic topography within the Alaşehir sub-basin.

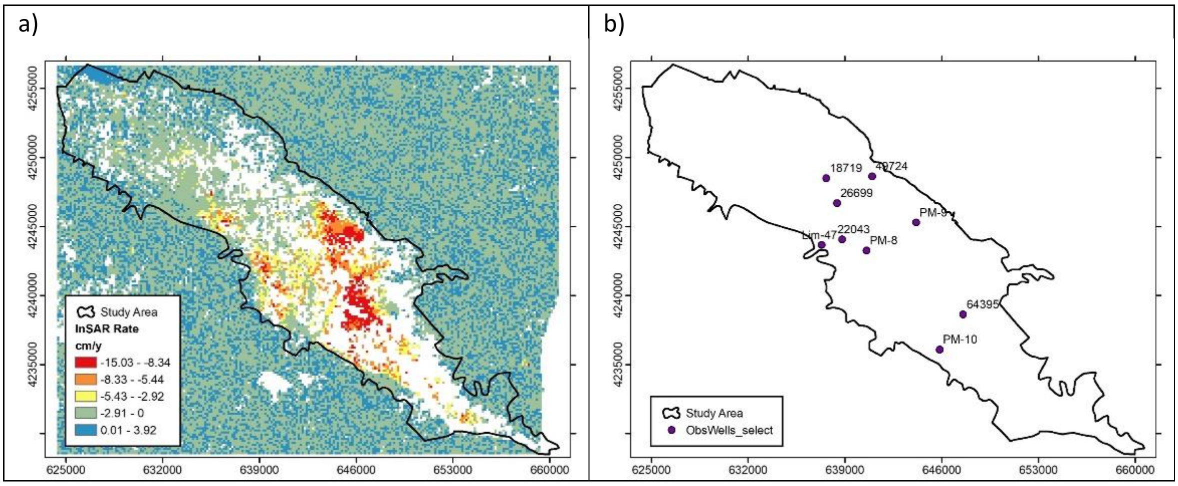

Figure 1. InSAR displacement rate (a) and location of the observation wells (b) in the Alaşehir-Sarıgöl Sub-Basin

Figure 1(b) depicts the spatial distribution of nine observation wells across the study area. Each well was assigned a buffer zone of 250 m, and the zonal mean of Persistent Scatterer (PS) values within these buffer zones were carefully calculated, resulting in a comprehensive overview of the wider region.

Figure 2 shows the analysis results for two of the nine monitoring wells, illustrating simulation hydraulic head values that correspond to the same time intervals as the InSAR-observed displacement values. As a result, stress-strain curves are generated for the nine observation wells. These curves provide a mean value for elastic storage coefficients, which were calculated by assessing the slope of each curve.

The spatial context of the calculated elastic storage coefficient values relative to the well locations is effectively demonstrated in Figure 3(a). The figure allows for a visual comprehension of the storage coefficients and their geographical distribution.

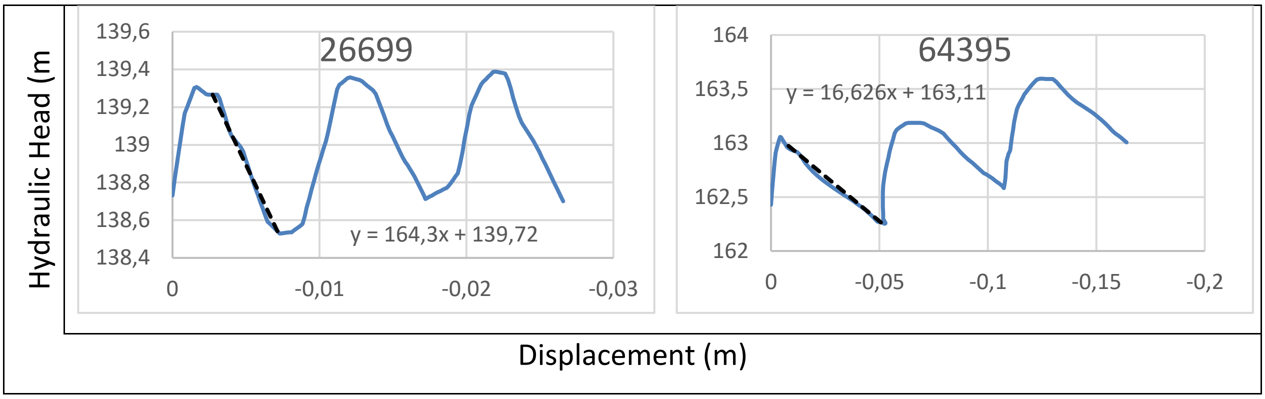

Figure 2. Stress-strain curves for the locations around the observation wells and slope lines representing the decrease in hydraulic head. Arbitrarily selected observation wells located in different regions

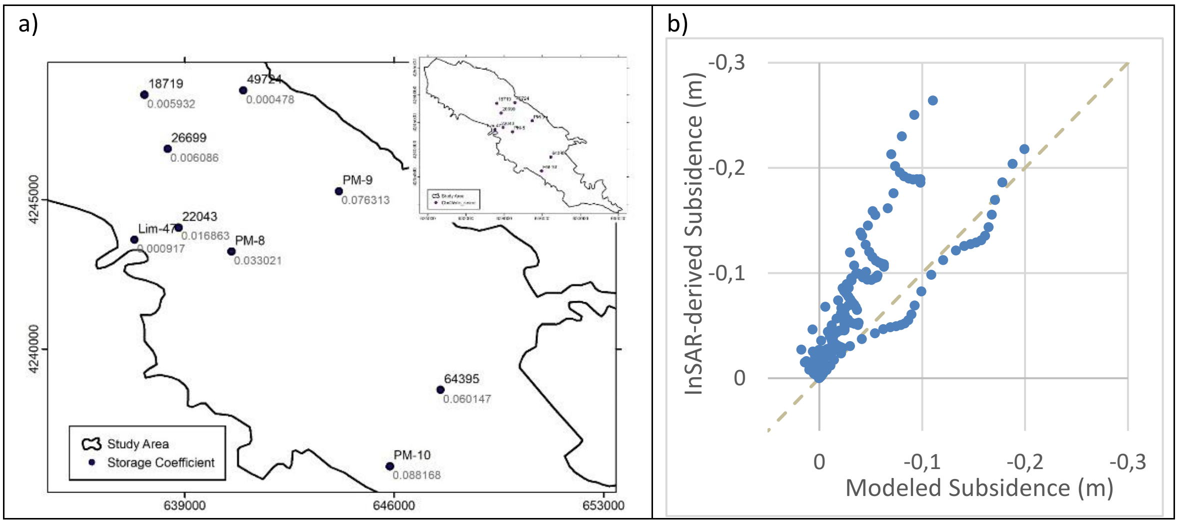

Figure 3. Storage coefficients (a) derived from stress-strain curves of observation wells and comparison of modeled subsidence versus InSAR-derived subsidence (b)

Finally, land subsidence was obtained for each time step defined between January 2019 and August 2021. Figure 3(b) shows the computed subsidence values, calculated from Equations 1-3 utilizing the computed storage coefficients, and compares them with the subsidence values obtained from InSAR measurements. In accordance with this relationship, the value of the mean absolute error (MAE) was determined to be 2.4 cm. Interestingly, the modeled subsidence appears to underestimate the subsidence represented by InSAR-derived measurements, suggesting further examination and analysis. This extensive range of analyses, covering remote sensing, hydrograph comparisons and modelling, considerably enhances our comprehension of the intricate interplay between geological and hydrological processes affecting the active terrain in the Alaşehir-Sarıgöl sub-basin.

4. CONCLUSIONS

Using the finite difference method, a groundwater flow model was conducted. The model was used to determine groundwater levels. Additionally, using InSAR, a technique for sensing ground surface movements, the ground settlements caused by changes in groundwater level across the model time span were identified. The storage coefficient was then calculated using the stress-strain curve derived from the InSAR displacement values corresponding to the groundwater levels in each observation well in the groundwater flow model. Therefore, using the storage coefficient and groundwater level drop factors, the settlement as an indicator of land subsidence was estimated. The relationship between InSAR and predicted settlement values were compared, and the mean absolute error (MAE) value was found to be 2.4 cm/y. This method allows approximate measurement of settlements due to changes in groundwater levels.

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KAYNAKLAR

Banton, O., & Bangoy, L. M. (1996). A new method to determine storage coefficient from pumping test recovery data. Groundwater, 34(5), 772-777.

Blanco-Sànchez, P., Mallorquí, J. J., Duque, S., & Monells, D. (2008). The Coherent Pixels Technique (CPT): An Advanced DInSAR Technique for Nonlinear Deformation Monitoring BT - Earth Sciences and Mathematics: Volume 1 (A. G. Camacho, J. I. Díaz, & J. Fernández (eds.); pp. 1167–1193). Birkhäuser Basel. https://doi.org/10.1007/978-3-7643-8907-9_10

Bonì, R., Meisina, C., Teatini, P., Zucca, F., Zoccarato, C., Franceschini, A., Ezquerro, P., Béjar-Pizarro, M., Antonio Fernández-Merodo, J., Guardiola-Albert, C., Luis Pastor, J., Tomás, R., & Herrera, G. (2020). 3D groundwater flow and deformation modelling of Madrid aquifer. Journal of Hydrology, 585, 124773. https://doi.org/10.1016/j.jhydrol.2020.124773

Chen, K. H., Hwang, C., Chang, L. C., & Ke, C. C. (2018). Short-time geodetic determination of aquifer storage coefficient in Taiwan. Journal of Geophysical Research: Solid Earth, 123(12), 10-987.

Chen, M., Tomás, R., Li, Z., Motagh, M., Li, T., Hu, L., Gong, H., Li, X., Yu, J., & Gong, X. (2016). Imaging land subsidence induced by groundwater extraction in Beijing (China) using satellite radar interferometry. Remote Sensing, 8(6), 1–21. https://doi.org/10.3390/rs8060468

Dragoni, W., & Sukhija, B. S. (2008). Climate change and groundwater: a short review. Geological Society, London, Special Publications, 288(1), 1-12.

Galloway, D. L., & Hoffmann, J. (2007). The application of satellite differential SAR interferometry-derived ground displacements in hydrogeology. Hydrogeology Journal, 15(1), 133–154. https://doi.org/10.1007/s10040-006-0121-5

Harbaugh, A. W. (2005). MODFLOW-2005, the US Geological Survey modular ground-water model: the ground-water flow process (Vol. 6). Reston, VA, USA: US Department of the Interior, US Geological Survey.

Hoffmann, J. (2003). The application of satellite radar interferometry to the study of land subsidence over developed aquifer systems. Stanford University.

Hoffmann, J., Leake, S. A., Galloway, D. L., & Wilson, A. M. (2003). MODFLOW-2000 Ground-Water Model: User Guide to the Subsidence and Aquifer-System Compaction(SUB) Package. Open-file Report. U. S. Geological Survey, (233), 56.

Navarro-Hernández, M. I., Tomás, R., Lopez-Sanchez, J. M., Cárdenas-Tristán, A., & Mallorquí, J. J. (2020). Spatial analysis of land subsidence in the San Luis potosi valley induced by aquifer overexploitation using the coherent pixels technique (CPT) and sentinel-1 insar observation. Remote Sensing, 12(22), 1–23. https://doi.org/10.3390/rs12223822

Ostad-Ali-Askari, K., & Shayannejad, M. (2021). Quantity and quality modelling of groundwater to manage water resources in Isfahan-Borkhar Aquifer. Environment, Development and Sustainability, 1-17.

Tomás, R., Herrera, G., Cooksley, G., & Mulas, J. (2011). Persistent Scatterer Interferometry subsidence data exploitation using spatial tools: The Vega Media of the Segura River Basin case study. Journal of Hydrology, 400(3–4), 411–428. https://doi.org/10.1016/j.jhydrol.2011.01.057

Tomás, R., Lopez-Sanchez, J. M., Delgado, J., & Mallorquí, J. J. (2006). Hydrological parameters of the vega media of the segura river aquifer (SE Spain) obtained by means of advanced DInSAR. International Geoscience and Remote Sensing Symposium (IGARSS), 2, 1553–1556. https://doi.org/10.1109/IGARSS.2006.400

Tonkul, S., Baba, A., Şimşek, C., Durukan, S., Demirkesen, A. C., & Tayfur, G. (2019). Groundwater recharge estimation using HYDRUS 1D model in Alaşehir sub-basin of Gediz Basin in Turkey. Environmental Monitoring and Assessment, 191(10), 610. https://doi.org/10.1007/s10661-019-7792-6

van Dam, Tonie, J. Wahr, and David Lavallée. "A comparison of annual vertical crustal displacements from GPS and Gravity Recovery and Climate Experiment (GRACE) over Europe." Journal of Geophysical Research: Solid Earth 112.B3 (2007).