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MODFLOW-Based Simulation of Groundwater Response to Rainfall in the Coastal Plain of Al-Hsain Coastal Basin, Syria

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Groundwater is an important factor in sustaining water supply in semi-arid coastal basins, where surface water resources are limited and climatic variability greatly affects availability. Rainfall events translated to groundwater recharge are of paramount importance for planning as well as for sustainable resource management in the Mediterranean catchment. The interaction between rainfall and groundwater level is particularly complex within areas of geological heterogeneity and seasonal climatic regimes. As valuable as this relationship is, it continues to be poorly understood in the most vulnerable areas, including western Syria. This research examines the dynamic interaction between rainfall and groundwater levels in the Al-Hsain Basin, a semi-arid coastal area in western Syria. A transient groundwater flow model was built with MODFLOW and calibrated against 4 y (2020–2024) of monthly data from 35 observation wells and local precipitation measurements. The model effectively replicated seasonal groundwater variations controlled largely by rain, and spatial variations related to geological heterogeneity. A (0–1) month time lag between rainfall maxima and groundwater response suggests delayed infiltration in the unsaturated zone. Model performance was tested with statistical and hydrograph analyses, illustrating excellent agreement against over 95 % of observed data. The results confirmed the model as it gave a hydraulic head distribution very similar to the monitoring wells data (variations of less than 0.10–0.25 m). Spatial maps and water balance overviews under wet and dry conditions proved the model's robustness under hydrological conditions. Despite some data limitations, this study offers helpful data on groundwater recharge processes and practical recommendations for improving water resource management in similar Mediterranean coastal settings.

1. Introduction

In regions with limited water, especially semi-arid areas, groundwater is a primary source. This becomes more important in coastal plains where aquifers are affected by short-term changes in weather. In the Syrian coastal zone, rainfall is the main source for recharging groundwater; it is hard to measure recharge directly (Scanlon et al., 2002), with annual values ranging from 800 mm in the lower parts to over 2,000 mm in the higher areas (Al-Faour and Fayyad, 2014). The rainfall helps to maintain springs and aquifers, but growing water use has increased the stress on these resources. This situation shows the need to better understand recharge, especially under increasing demand and climatic variability conditions. Recharge amounts change depending on climate and geology. In the north of Syria, recharge is about 10–15 % of rainfall (~300 mm) (Abou and Merkel, 2014). Recent studies emphasized that the accuracy of groundwater recharge estimation in arid regions is highly sensitive to input data resolution and variability, particularly regarding precipitation and soil characteristics (Ajjur and Di Lorenzo, 2024).

Some wetter Mediterranean locations may get 30–50 % recharge when annual rainfall exceeds 300 mm. In other continental regions is less (Chappon et al., 2024), but in arid regions, recharge becomes almost zero (Dvory et al., 2018). These examples show why each region needs local analysis based on climate and ground features, but models have become very important in studying groundwater behavior. These models can show how rainwater moves underground. When appropriately adjusted, they help estimate key values like hydraulic conductivity (K), storage coefficient (S), and recharge rate. One of the most used models is MODFLOW,

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developed by the USGS. It can include recharge, wells, springs, and runoff (Harbaugh, 2005). Anderson et al. (2015) extended MODFLOW usage by integrating streams, wells, and recharge components into regional-scale models, demonstrating its applicability in semi-arid coastal zones similar to Syria. MODFLOW was used to compare traditional and distributed recharge inputs, showing reliable performance with error margins under 5 % (Álvarez-Gómez et al., 2024). An integrated SWAT–MODFLOW model effectively simulated climate-driven recharge variations across space and time (Panagiotopoulos et al., 2024).

The relationship between rainfall and groundwater levels remains understudied in many vulnerable regions, particularly in areas with complex geological conditions and strong seasonal climate variations, such as western Syria. Understanding how rainfall events translate into groundwater recharge is important for sustainable water management, especially in Mediterranean regions where surface water is scarce and interannual variability is high. This study uses a transient MODFLOW model to investigate the dynamic interaction between rainfall and groundwater levels in the Al-Hsain coastal basin in western Syria. The model is calibrated using 4 y of monthly records from 35 observation wells and local precipitation data. It aims to identify recharge behavior, quantify seasonal groundwater changes, and provide practical recommendations to support long-term water planning in similarly stressed Mediterranean settings.

2. Study area and data

The Al-Hsain Basin is situated along the Syrian coast within Tartous Governorate, extending from the Syrian-Lebanese border in the south to the confluence of the Hsain and Abrash Rivers in the north. The study area is approximately 10.86 km², characterized by relatively flat topography and minimal human activity. The region falls under a Mediterranean climate, with rainfall concentrated between November and March, while the rest of the year remains dry. Annual precipitation varies spatially and temporally, averaging around 1,000 mm near the coast and gradually decreasing inland.

Geologically, the basin comprises Quaternary formations along the coastal plain and Neogene formations toward the interior. These formations play a key role in controlling the hydrodynamic behavior of the unconfined aquifer, which serves as the main groundwater reservoir in the area. Groundwater recharge is predominantly driven by rainfall, and the aquifer is generally shallow and unconfined, allowing for direct vertical infiltration.

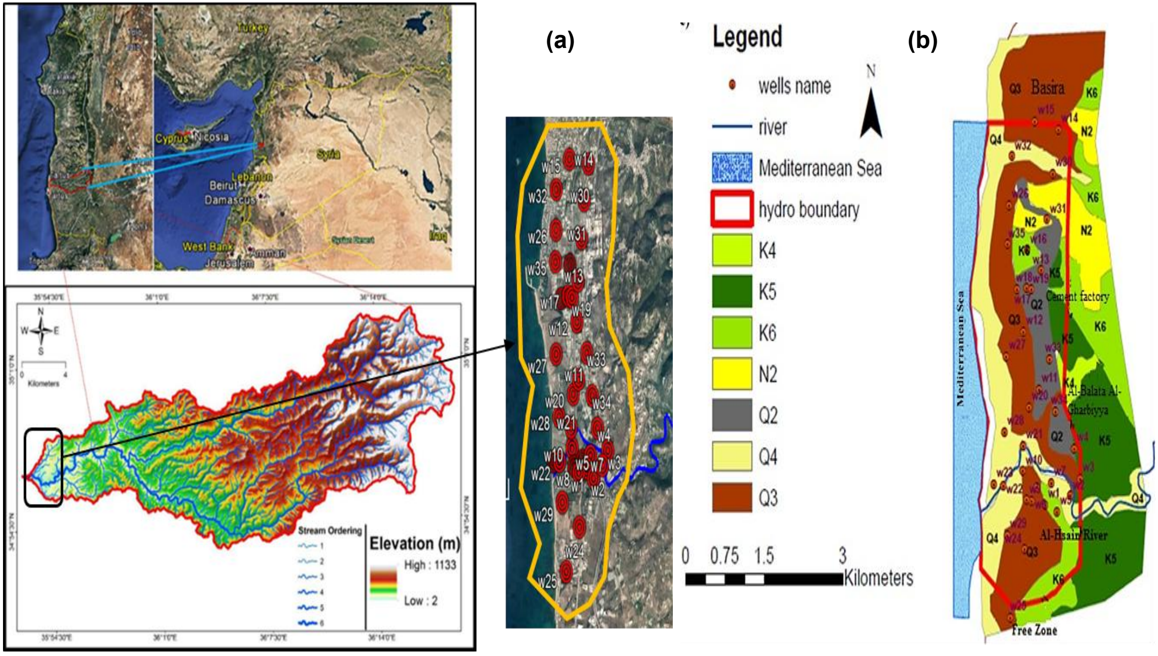

Figure 1. Study area: location, hydrogeology, and observation well distribution. (a) Location of the Al-Hsain Basin in the Syrian coastal region, showing topography, observation wells, and stream network. (b) Distribution of observation wells (w1–w35) across the main geological formations in the Al-Hsain Basin, including the coastline, Al-Hsain River, and hydrogeological boundaries

The dataset used in this study includes monthly groundwater level records from 35 observation wells distributed across the basin, collected over four hydrological years (March 2020 to March 2024). Monthly precipitation data were also obtained from the Tartous Meteorological Station, the closest official station to the study area. The spatial distribution of wells and the rainfall station is shown in Figure 1(a), while (b) presents a general hydrogeological map of the region.

3. Methodology

A numerical groundwater flow model was developed using the MODFLOW code within the GMS (Groundwater Modeling System) environment to simulate the spatiotemporal response of the shallow aquifer to rainfall in the Al-Hsain Basin. The overall workflow of the modeling process, from data collection to result analysis, is presented in Figure 2. The model domain was discretized using a finite difference grid consisting of one unconfined layer that represents the Quaternary and Neogene formations. The model boundaries were assigned based on hydrological and topographic limits: specified-head boundaries were applied along the coastal side and river outlets, while no-flow boundaries were used along watershed divides. Figure 3(a), (b) illustrates the model grid design, boundary conditions, and well locations, including detailed refinement levels in selected areas. Hydraulic conductivity values were assigned spatially based on available geological reports and literature and further adjusted during calibration. The spatial distribution of these values is shown in Figure 4(a). Groundwater recharge was defined as temporally variable and spatially distributed zones, reflecting geological and land-use characteristics, as shown in Figure 4(b). Recharge was calculated monthly using rainfall data from the Tartous meteorological station and distributed across 18 recharge zones. All 35 observation wells were used in the model, and actual monthly abstraction values were incorporated based on field records and verified with local user reports. The model was simulated under transient conditions using monthly stress periods covering four hydrological years (March 2020 – March 2024). Calibration was performed manually using a trial-and-error approach by adjusting hydrogeological parameters to minimize residuals between observed and simulated heads, and its performance was evaluated visually and statistically using hydrograph comparisons and indicators such as Root Mean Square Error (RMSE) and Mean Error (ME). The model assumes homogeneous recharge within each zone and does not account for evapotranspiration or data limitations. The interaction between the river and the groundwater reservoir was included through specified head or flow boundary conditions based on field measurements.

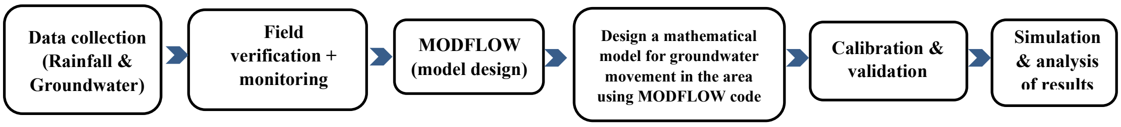

Figure 2. Workflow diagram of the groundwater modeling and analysis process

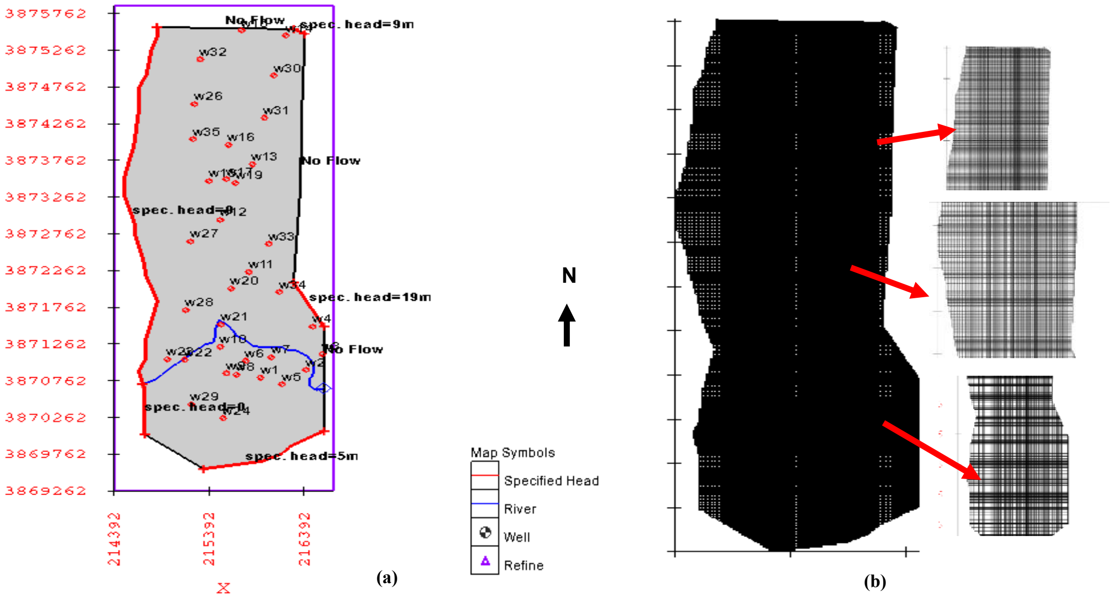

Figure 3. Model setup and input parameters. (a) Assigned boundary conditions and distribution of observation wells in the MODFLOW model. (b) Model grid refinement showing spatial resolution across the domain

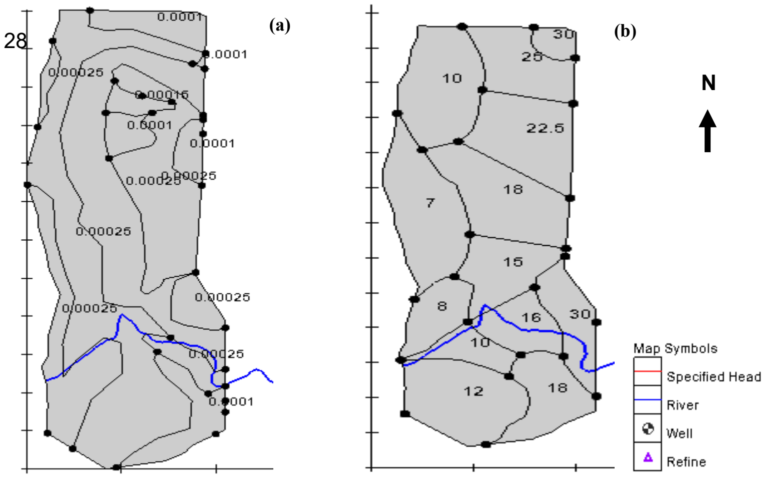

Figure 4. (a) Spatial distribution of hydraulic conductivity (K). (b) Delineated recharge zones used in the model

The groundwater flow simulation is based on the finite difference method (FDM), which discretizes the aquifer system into a three-dimensional grid of cells. The governing equation used is the transient three-dimensional partial differential equation of groundwater flow in heterogeneous and anisotropic media, as formulated by the U.S. Geological Survey (McDonald and Harbaugh, 1988):

$$\frac{\partial}{\partial x}\left(k_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(k_{zz}\frac{\partial h}{\partial z}\right)-W=S_S\frac{\partial h}{\partial t} \tag{1}$$

where: k_{xx}, k_{yy}, k_{zz} : hydraulic conductivities in x, y, and z directions [m/s], h: hydraulic head [m], S_S: specific storage [1/m], W: volumetric flux per unit volume representing recharge or abstraction [1/s], t: time [s]. Hydraulic conductivity and specific storage are spatially distributed and assumed constant within each cell. Recharge and boundary conditions may vary with time. Therefore, the model simulation is divided into stress periods, each composed of several time steps to capture transient system behavior.

4. Results

The transient MODFLOW model was calibrated manually using a trial-and-error approach, which involved iterative adjustment of key hydrogeological parameters such as horizontal hydraulic conductivity, specific yield, and recharge rates. The objective was to minimize the residuals between simulated and observed groundwater levels across the model domain. The calibration process utilized 4 y of monthly groundwater data (March 2020 – March 2024) from 35 observation wells distributed across the Al-Hsain Basin. In addition, actual pumping rates for each well were incorporated into the model, ensuring a realistic representation of groundwater abstraction impacts during the simulation period.

Calibration effectiveness was assessed using both spatial and statistical performance indicators. Simulated groundwater heads were directly compared with observed heads under representative wet and dry conditions. Residual head maps show the spatial distribution of differences between observed and simulated groundwater levels. These residuals were generally low, with most wells showing errors of less than 0.25 m and very few exceeding 0.5 m (Figure 5(a), (b)). These results indicate a high level of spatial accuracy across diverse hydrogeological zones, including areas with varying recharge rates and lithologies. Root Mean Square Error (RMSE) values across the observation network were consistently below 1.0 m, and mean errors remained near zero. These metrics demonstrate a strong correlation and a low degree of dispersion between observed and simulated data, validating the model's ability to replicate actual groundwater behavior under wet and dry seasonal conditions.

The calibrated model was used to simulate groundwater dynamics over 4 y (March 2020 – March 2024), highlighting spatial and temporal variations in groundwater levels in response to rainfall. A clear and consistent seasonal fluctuation in groundwater levels was observed throughout the simulation. Water levels generally rose during the rainy season (November to April), followed by a gradual decline during the dry summer months (May to October), in line with expected patterns in Mediterranean climates. An important observation from the temporal analysis was a delayed groundwater response following rainfall events. Across the basin, a time lag of approximately (0–1) month was detected between peak rainfall and corresponding rises in groundwater levels. This lag was particularly noticeable in wells located in areas with thicker unsaturated zones or lower hydraulic conductivities, where vertical percolation through the vadose zone takes longer.

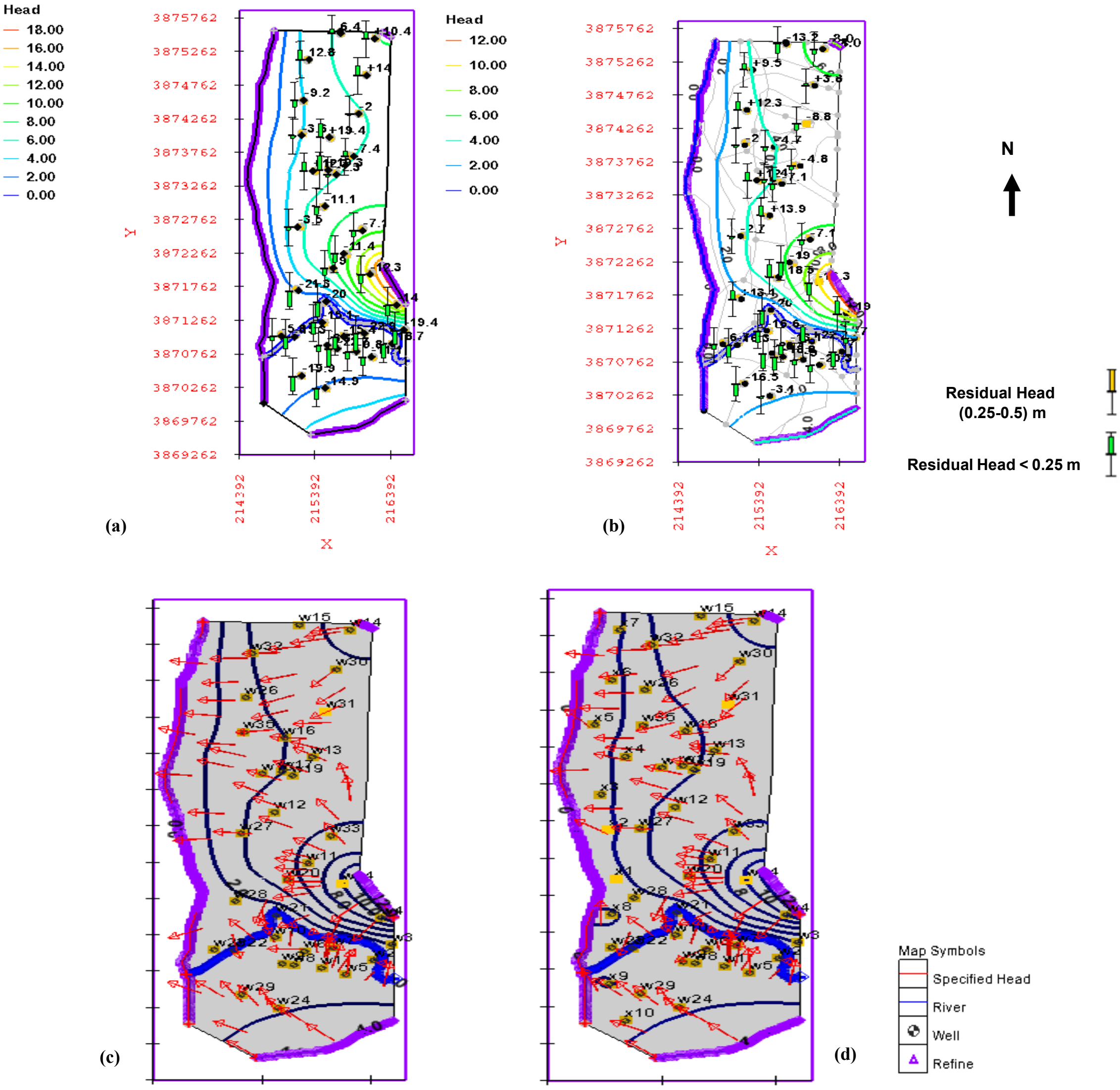

Figure 5. Residual differences between simulated and observed groundwater heads during model calibration (a, b), and simulated groundwater heads with flow directions under steady-state conditions (c, d): (a) March 2021 residuals; (b) August 2020 residuals; (c) March 2021 wet month; (d) August 2020 dry month

This behavior is consistent with known recharge dynamics in semi-arid Mediterranean settings, where the infiltration of precipitation is not immediate and depends strongly on soil moisture conditions, lithology, and depth to the water table. Spatial variation in groundwater response was also evident across different geological units. Wells located in Quaternary formations near the coastal plain exhibited quicker and more pronounced responses to rainfall, while those in Neogene formations further inland responded more slowly and gradually. This behavior highlights the influence of geological heterogeneity on recharge rates and storage dynamics. Figure 4(c) and (d) illustrate spatial groundwater head distributions during representative wet and dry months, clearly showing seasonal contrasts across the basin. The model successfully replicated observed groundwater patterns across hydrological conditions, reinforcing its reliability. Minor residual errors persisted near river channels and recharge boundaries, but the errors remained low and within acceptable limits.

5. Conclusion

This study demonstrated the effectiveness of using a transient numerical groundwater flow model (MODFLOW) to simulate groundwater levels' spatial and temporal behavior in response to rainfall in the Al-Hsain Basin, a semi-arid Mediterranean coastal region in western Syria. The model was calibrated using **4 y** (March 2020 – March 2024) of monthly groundwater level data from 35 observation wells and corresponding rainfall records, resulting in a robust representation of the unconfined aquifer system. The calibrated model successfully reproduced observed groundwater dynamics, including seasonal fluctuations and spatial variations in recharge response. A time lag of approximately (0–1) month was identified between peak rainfall events and corresponding rises in groundwater levels, primarily due to infiltration delays in the unsaturated zone and geological heterogeneity. RMSE values across the observation network were consistently below 1.0 m, and over 95 % of wells exhibited residuals under 0.25 m, indicating high spatial and temporal accuracy. Recharge in the basin was confirmed to be driven primarily by direct precipitation, with spatial variation influenced by aquifer lithology. Wells in Quaternary deposits showed faster and more pronounced responses, while those in deeper Neogene formations responded more gradually. Groundwater head maps for wet and dry months revealed distinct seasonal contrasts, with water level differences ranging from (1.5 to 3.2) m in some locations between peak recharge and peak abstraction periods. Despite some limitations in data coverage and local-scale heterogeneity, the model showed strong agreement with field measurements and proved reliable as a decision-support tool, offering valuable insights into recharge behavior and groundwater storage dynamics of Mediterranean aquifer systems while underscoring the critical role of long-term monitoring in model development and validation. Overall, this study provides a solid basis for managing groundwater resources in the Al-Hsain Basin and other semi-arid coastal areas, presenting a transferable framework for sustainable water management in regions facing increasing demand and climate-induced stress.

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References

Abou D., Merkel B., 2014, Groundwater recharge estimation in arid regions: A case study from northern Syria. Environmental Earth Sciences, 71(10), 4465–4477, DOI: 10.1007/s12665-013-2805-3.

Ajjur S.B., Di Lorenzo E., 2024, Sensitivity of Groundwater Recharge Assessment to Input Data in Arid Areas. Hydrology, 11(2), 28, DOI: 10.3390/hydrology11020028.

Al-Faour A., Fayyad M., 2014, Climate characteristics and water resources in the coastal region of Syria. Arabian Journal of Geosciences, 7(12), 5099–5110, DOI: 10.1007/s40710-014-0043-5.

Álvarez-Gómez J.A., Jiménez-Alcántara M.M., González-Ramón A., 2024, Comparison between MODFLOW groundwater modeling with traditional and distributed recharge. Hydrology, 11(1), 9, DOI: 10.3390/hydrology11010009.

Anderson M.P., Woessner W.W., Hunt R.J., 2015, Applied groundwater modeling: Simulation of flow and advective transport. 2nd ed, Academic Press, Cambridge, United Kingdom, 535–564.

Chappon M., Madarász K., Bene K., 2024, Assessing the Long-Term Groundwater Level Dynamics in Szigetköz, Hungary. Chemical Engineering Transactions, 114, 859–864, DOI: 10.3303/CET24114144.

Dvory N.Z., Yechieli Y., Shalev E., Kiflawi M., 2018, Estimating groundwater recharge using water-table fluctuations and modeling in a Mediterranean climate. Hydrological Processes, 32(4), 511–526, DOI: 10.1002/hyp.11423.

Harbaugh A.W., 2005, MODFLOW-2005, The U.S. Geological Survey Modular Groundwater Model—The Groundwater Flow Process (Techniques and Methods 6-A16). U.S. Geological Survey, <https://pubs.usgs.gov/tm/2005/tm6A16>, accessed 18.10.2025.

McDonald M.G., Harbaugh A.W., 1988, A modular three-dimensional finite-difference groundwater flow model (Techniques of Water-Resources Investigations, Book 6, Chapter A1). U.S. Geological Survey, <https://pubs.usgs.gov/twri/twri6a1>, accessed 18.10.2025.

Panagiotopoulos D., Kourgialas N.N., Karatzas G.P., 2024, Assessment of future climate change impacts on groundwater – Integration of MODFLOW and SWAT models. Water, 16(3), 419, DOI: 10.3390/w16030419.

Scanlon B.R., Healy R.W., Cook P.G., 2002, Choosing appropriate techniques for quantifying groundwater recharge. Hydrogeology Journal, 10(1), 18–39, DOI: 10.1007/s10040-005-0436-6.