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Conceptual Modflow Model Application with Boundary Condition Analysis

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ABSTRACT: In this study, groundwater flow modeling of the aquifer in the Porsuk Basin, located in the Eskisehir province of Turkey, was conducted using the MODFLOW modeling method and the Groundwater Modeling System (GMS) software interface. The modeling was performed using the finite difference method under the assumption of steady flow, incorporating well data, aquifer boundaries, topographic elevations, riverbed data, and hydraulic parameters from the 1971 water year. This study provided insights into changes in groundwater over time and yielded a comprehensive water budget. By creating a three-dimensional solid model of the Porsuk Basin aquifer, general information about the region's hydrogeology was obtained. The results are expected to play a significant role in identifying potential drilling areas for groundwater extraction. Since the modeling utilizes objects from geographic information systems, it will enhance visualization of the regional structure for researchers, allowing them to observe the topographic features of the area in three dimensions. Additionally, it is anticipated that the groundwater conceptual model will inform drilling studies and serve as a foundation for research on groundwater transport and pollution.

KEYWORDS: Groundwater, Groundwater Modeling, Modflow, GMS, Porsuk Basin

I. INTRODUCTION

Despite the increasing demand for water due to rapid population growth in recent years, the inadequate availability of suitable resources and the challenges arising from excessive use and various pollution factors related to ongoing industrial and agricultural activities have necessitated serious measures for effective water resource management. Excessive consumption and pollution have led to insufficient surface water, making groundwater usage essential. To optimize the use of groundwater, which is becoming increasingly important, it is crucial to understand its behavior over time and across different locations. This understanding is vital for the effective management of groundwater resources [1].

Groundwater resources are widely preferred for drinking water supply due to their low sensitivity to pollution and high reliability. Groundwater is generally unaffected by short-term drought events, making it a dependable source of drinking water. However, obtaining precise information about the aquifers that contain groundwater is challenging, as they are not visible like surface waters. Groundwater models provide a framework for water resource planning and management in (semi-)arid regions. Today, numerical modeling is recognized as an important tool for examining groundwater resources. In these models, a simplified mathematical representation of a groundwater system is typically solved using computer programs. They incorporate data from geology, hydrogeology, hydrology, climatology, geography, and more to simulate the quantity and quality of groundwater resources. However, collecting this information can be difficult and often involves a high degree of uncertainty, especially in developing countries. The quality of the data used as input in groundwater models significantly affects the model results. Therefore, accurate input data is essential to achieve reliable outcomes [2],[3],[4].

In this study, a three-dimensional, block-centered (cell-centered), steady-state finite difference model, MODFLOW, was employed to determine the amount of groundwater in the Middle Porsuk Region of the Porsuk Basin, located in the Eskisehir province of Turkey.

MODFLOW is recognized as an international standard for simulating and predicting groundwater conditions. It encompasses two main approaches: steady state and transient state. The semi-transient approach allows for the consideration of changes in parameters over the simulation period [5],[6],[7].

Available data and measurements were analyzed for quality before being prepared for use in modeling the Porsuk Basin aquifer. Data were obtained from the General Directorate of State Hydraulic Works (DSI) and the General Directorate of Meteorology (MGM) to create the aquifer model. In the hydrogeological context of the basin, the "Eskişehir ve İnönü Ovası Hidrojeolojik Etüt Raporu" was prepared by the Geotechnical Services and Groundwater Department of the General Directorate of State Hydraulic Works in 1975 [8].

The study aimed to conduct basin aquifer modeling using the GMS program to eliminate uncertainties in the groundwater usage of the Porsuk Basin, to manage and monitor potential future changes, and to optimize the use of its reserves.

II. MATERIALS AND METHODS

A. Study Area

The surface area of the Porsuk Basin is 11,114 km². Located between 29° 38' and 31° 59' east longitudes and 38° 44' and 39° 99' north latitudes, the basin extends 202 km in the east-west direction and 135 km in the north-south direction. Over 60% of the surface waters in this mountainous basin are collected by the Porsuk stream and its tributaries (Figure 1). After traveling 436 km within the basin, the Porsuk stream flows into the Sakarya River at an elevation of 660 m. The basin's water potential is low, with a long-term average annual rainfall of only 451 mm [9], [10].

Figure 1. Porsuk basin.

B. Groundwater Modeling of Porsuk Aquifer

GMS is a graphical user interface for various groundwater models, including FEMWATER, SEEP2D, SEAM3D, MT3DMS, MODFLOW, RT3D, MODPATH, MODAEM, and SEAWAT. In this study, the MODFLOW model was chosen due to its high efficiency and widespread application in groundwater research. The model simulates flow in three dimensions using the finite difference method for both steady-state and transient conditions [11],[12].

MODFLOW is a finite difference flow model that combines two fundamental equations—the Darcy equation and the principle of conservation of mass (or mass balance)—to simulate groundwater flow in three dimensions. The latest version, known as MODFLOW-2005, builds upon the original model first developed by the USGS and published in 1984. The program is written in Fortran 90 and includes numerous packages and modules [13],[14].

MODFLOW-2005 is highly capable of modeling complex groundwater issues. The program allows for the three-dimensional simulation of hydrogeological processes with various structures, enabling researchers to model areas that are intricate and involve multiple parameters. It can represent flows entering and exiting the system through processes such as recharge, discharge, pumping, drainage, and evapotranspiration from streams. Researchers can analyze model outputs, including changes in groundwater levels, flow directions, and hydraulic head distribution [15],[16].

MODFLOW-2005 calculates the numerical solution to the time-dependent three-dimensional groundwater flow equation, as represented by the equation below:

$$\frac{\partial}{\partial x}\left(Kxx\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(Kyy\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(Kzz\frac{\partial h}{\partial z}\right)+W=Ss\frac{\partial h}{\partial t}$$

In the equation, K_{xx}, K_{yy} and K_{zz} are the hydraulic conductivities along the x, y, z axes respectively (LT^{-1}), h: hydraulic head (L), W: displacement per unit volume at the water inlet or outlet (T^{-1}), SS: specific storage coefficient (L^{-1}) and t is time [15].

MODFLOW-2005 discretizes the aquifer using a finite difference method, employing grid cells to calculate groundwater levels and flows. The finite difference grid network must align with the axes of hydraulic conductivity. The cells are numbered based on indices represented by the letters i (row index), j (column index), and k (layer index) [16].

MODFLOW-2005 calculates the numerical solution to the time-dependent three-dimensional groundwater flow equation. Horizontal discretization is achieved by creating a rectangular grid network consisting of rows and columns, where rows are aligned parallel to the x-axis and columns are aligned parallel to the y-axis. The row index i decreases in the y direction, while the column index j increases in the x direction. Vertical discretization is defined by layers that are aligned parallel to the horizontal plane. The layer index k increases in the z direction, meaning the top layer of the model corresponds to k=1 The upper left cell in each layer corresponds to the first row (i=1) and the first column (j=1). The layers can have either constant or variable thickness [16].

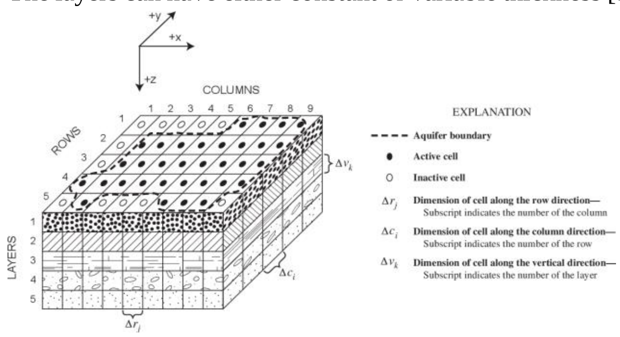

Figure 2. Discretized aquifer system [16].

The cells used to simulate the boundary conditions of the model are divided into two categories:

- specific hydraulic load cells
- non-flow cells.

In the model's data entry, the values of hydraulic loads are specified. These values remain unchanged unless modifications are made in the data entry for time and stress periods. Non-flow cells serve as boundary separators for the model, where no flow is permitted in or out. Groundwater is not calculated in these non-flow cells. The remaining cells are variable hydraulic load cells, where hydraulic loads are calculated and can change over time [17],[18].

C. Datasets

Hydraulic and hydrological data were obtained from the General Directorate of State Hydraulic Works (DSI) and the General Directorate of Meteorology (MGM). When creating the boundary conditions and grid networks of the model, the boundaries where the aquifer is in direct hydraulic connection with the Porsuk stream were defined as fixed-determined level boundaries. In the model, the springs representing the Porsuk stream are assigned a constant height, using the water level of the Porsuk stream as the fixed elevation value. The arcs surrounding the basin, which represent permeable and impermeable zones, are defined as non-flow boundaries.

A total of 26 wells from the hydrogeological map were transferred to the model, defined according to their coordinates and elevation values. Additionally, 6 pumping wells were incorporated into the model. For modeling purposes, topographic data of the land surface was obtained using a digital elevation model created on the GIS platform. Transmissibility values were calculated by the program by inputting constant values for the horizontal hydraulic conductivity, as well as for the lower and upper layers used in the modeling. The initial horizontal hydraulic conductivity value entered the model is the average derived from the wells. During the calibration phase of the modeling process, hydraulic conductivity and recharge values were calibrated using the PEST method.

III. GROUNDWATER MODELING OF PORSUK AQUIFER

The hydrogeological map shown in Figure 3 was imported into the GMS software as a base, with coordinates set to UTM Zone 36N, ED 1950. Conceptual modeling studies were initiated from this point. The modeling process began with steady-state simulations, followed by both manual and automatic calibration using the PEST method. After determining the parameters, the model was subsequently adjusted to simulate transient conditions for groundwater flow.

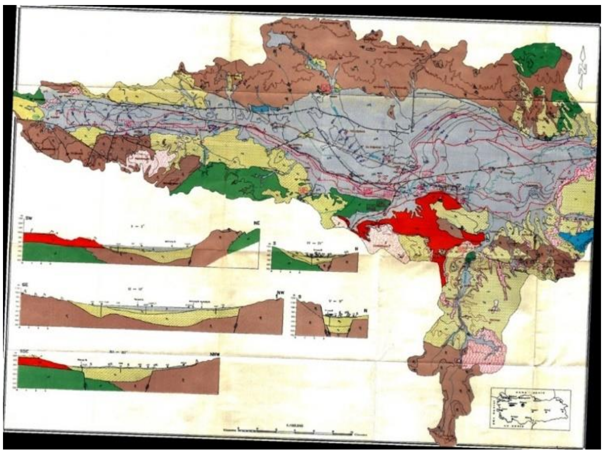

Figure 3. Hydrogeological map of the region [4].

A. Steady state

In the simulation, arcs representing no-flow boundaries are defined as such. The Sarısu River, located in the İnönü Plain, and the Porsuk Stream at their junction have been designated as fixed level boundaries. The starting, junction, and endpoint of the arcs are specified using water elevation data (Figure 4).

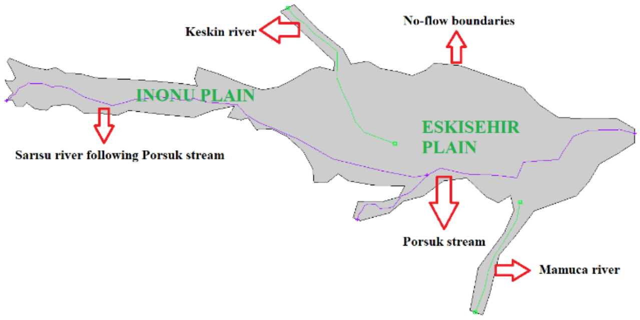

Figure 4. Model structure in GMS software.

In the steady-state modeling, the model boundaries were established within the defined limits, and the average elevation of the study area was incorporated. The elevation values were determined using GIS tools. As part of the resource inputs, wells, constant head boundaries (CHD), and dry stream beds were included in the model [19]. A total of 26 wells from the hydrogeological map were integrated into the model according to their coordinates and elevation values. The model requires both elevation (Z) and flow rate values for the wells. Since the flow is drawn from the wells, flow rates are entered as negative values. Information about the wells transferred to the model is provided in Table 1.

Table 1. Wells [4]

Well no	X	Y	Z (m)	Flow (m^3/d)
2964-A	290371.37	4406239.95	786.3	3888
3184	297076.32	4402891.63	779.4	3888
5007	282301.17	4406453.94	808.6	691.2
5586	274597.36	4407055.57	811.7	172.8
5587-C	272954.19	4409524.35	806	1036.8
5590/A	247732.94	4413220.17	854.6	216
8049	286285.56	4407395.30	792	604.8
8071	286720.64	4404570.17	790	432
81	279082.70	4406505.13	802	864
1	289020.50	4410102.34	785	172.8
2	292080.74	4411291.60	783	216
3	297014.71	4410445.47	781	475.2
4	296416.26	4407668.60	780	864
5	296383.03	4404295.27	786	1123.2
6	300862.62	4407808.03	778	4320
7	305502.49	4408891.69	775	1296
23	292922.70	4405431.24	787	2592
2	251862.01	4412043.06	837	2419.2
4	257477.73	4412126.63	824	1728
5	260986.62	4413258.90	820	172.8

6	262726.16	4411182.08	818	432
7	267019.22	4412170.75	816	1036.8
9	271450.23	4409535.47	806	1728
10	274642.03	4408453.86	803	864
11	275861.10	4406121.43	813	1728
12	279567.77	4405121.74	797	1296

The model was developed to incorporate the aquifer layer and simulate groundwater movement within this layer. It was defined as a single layer, with specific height values established for both its upper and lower boundaries. To represent hydraulic conductivity, distinct zones were delineated based on values obtained from hydrogeological survey studies. The model is categorized into two regions concerning hydraulic conductivity. The first region corresponds to the area representing the river flow environment, while the remaining area encompasses other land cover types.

The hydraulic conductivity values incorporated into the model were initially entered as approximate values based on a defined range. Subsequently, these values were calibrated using the values obtained for the storage rate, allowing for the determination of the most accurate representation of reality.

Within the framework of recharge, another aspect of the model, the modeling area is divided into five distinct zones. This classification is based on data from the Eskişehir and İnönü Plains Hydrogeological Survey Report [8];

Table 2. Inonu plain recharge [8]

In	**x 10^6 m^3/y**	**Out**	**x 10^6 m^3/y**
Precipitation	2	To Sarısu river	3.5
Percolation from surface runoff	1		
Lateral	0.5		
Total	3.5		3.5

Specific storage refers to the ability of an aquifer or water retention medium to store water per unit volume, typically expressed in terms of m^3/m^3. It is a critical parameter for understanding how water moves and is stored within an aquifer. When water is stored in an aquifer, changes in groundwater levels are reflected in the filling or draining of pore spaces. High specific storage indicates that the aquifer can retain more water, which is essential for sustaining groundwater supplies, especially in regions dependent on aquifers for their water resources [20],[21],[22].

The interactions among precipitation, runoff, and evaporation are vital components of the hydrological cycle that influence specific storage. Precipitation replenishes aquifers, while runoff transports water through surface channels. Evaporation, on the other hand, can lead to water loss from the system. High evaporation rates can deplete the water stored in an aquifer, particularly when specific storage is low, resulting in declining groundwater levels. Understanding these relationships is crucial for effective water resource management and ensuring the sustainability of groundwater supplies in the face of changing climatic conditions [23],[24],[25].

Upon calculation, the average recharge rate for the region encompassing the Inonu Plain is determined to be approximately 0.000095 m/d.

Table 3. Eskisehir plain recharge [8]

In	**x 10^6 m^3/y**	**Out**	**x 10^6 m^3/y**
Precipitation	17.5	To Porsuk stream	116
Percolation from surface runoff	10	Artificial	16.5
Lateral	81		
Total	24		

***Model results before steady-state calibration*:** As a result of running the model, the water table was obtained (Figure 5). To ensure the accuracy of the results, it is essential to calibrate the model. In this study, calibration was conducted using both manual methods and the PEST method. During both calibration processes, the observed flow and water table heights from the observation wells were utilized. These data were sourced from the hydrogeological survey report and corresponding maps, and subsequently integrated into the model. Calibration efforts focused on adjusting the hydraulic conductivity and recharge values of the model.

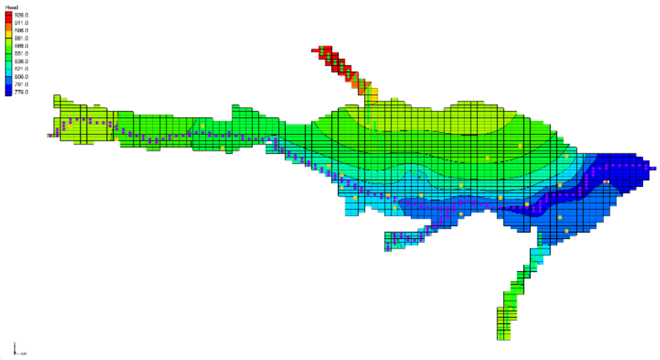

Figure 5. Steady state (before calibration) modeling result.

***Steady state calibration*:** Before a groundwater model can be employed for predictive purposes, it is crucial to demonstrate its ability to accurately simulate observed aquifer behavior. Calibration is a systematic process wherein specific model parameters, such as recharge and hydraulic conductivity, are varied, and the model is repeatedly executed until the calculated results align with field-observed values within an acceptable level of accuracy.

***Manuel calibration*:** Water table elevations in observation wells and observed flows in the river represent two key types of observational data utilized during the calibration process. To facilitate this calibration study, a comprehensive scope of observations was established for the model.

The total flow rate measured in Cavlum village, located in the Porsuk region near the eastern exit point of the model, was recorded as 9.4 m³/sec. The margin of error for this observed flow was established at 5%. While this value may vary based on the parameters and conditions specific to each model, it is generally recommended to adopt a 5% margin of error in GMS sources [25].

Figure 6. Manual calibration success status.

The components of the calibration target are illustrated in Figure 7. The center of the target represents the observed value, while the upper limit corresponds to the observed value plus the specified range, and the lower limit corresponds to the observed value minus the range. The colored bar indicates the error. If the bar is entirely within the target, it is displayed in green. If the bar is outside the target but the error is less than 200%, it is shown in yellow. If the error exceeds 200%, the bar is depicted in red. In this instance, the bar should be green [25].

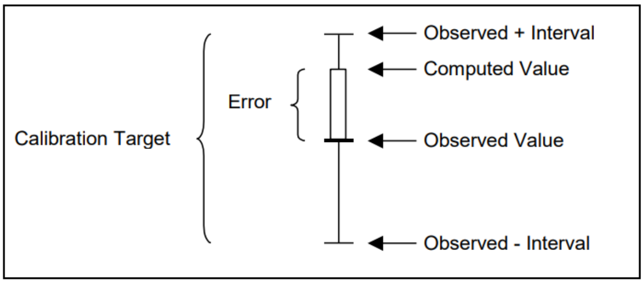

Figure 7. Calibration target [25].

After defining the observation points, the observed flow values can be inputted. These observed flows are directly assigned to arcs and polygons within the source scope of the conceptual model. MODFLOW calculates the flow from the aquifer to the stream, and this calculated flow value will be compared to the observed flow [26].

Using the manual calibration method, efforts are made to minimize the error level as much as possible. Subsequently, the PEST automatic calibration method is employed to enhance sensitivity and improve the overall accuracy of the model [18].

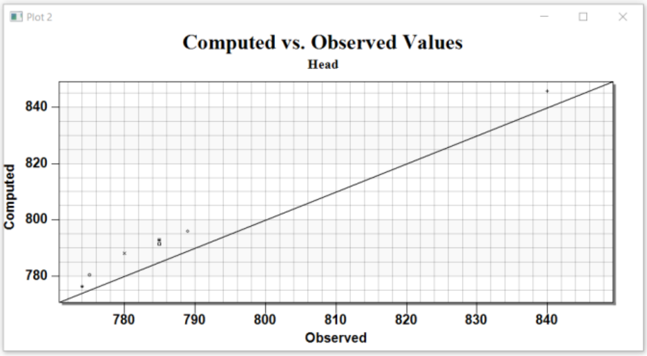

Figure 8. Computed vs. observed values.

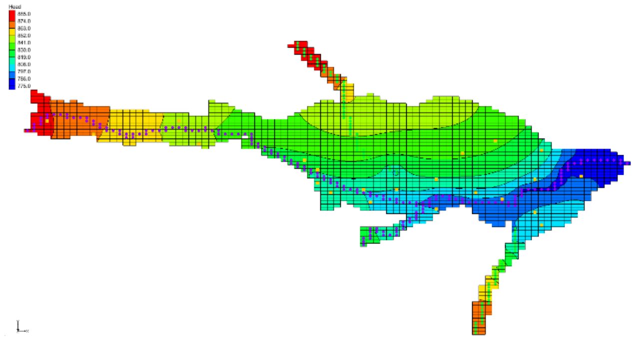

Figure 9. Modeling result after steady-state manual calibration.

***Calibration with PEST method*:** In many cases, calibration can be conducted more rapidly using the PEST method. PEST is a complementary GMS module that automates the parameter estimation process. Calibration systematically adjusts a set of user-defined input parameters until the difference between calculated and observed values is minimized [18],[19].

The model incorporates observed flow data for the stream and observed loads from a set of scattered observations. The conceptual model for the site consists of a series of recharge and hydraulic conductivity zones. These zones are designated as parameters, and an inverse modeling approach is employed to identify a range of recharge and hydraulic conductivity values that minimize calibration error [18],[19].

PEST involves defining hydraulic conductivity and recharge zones, marking these zones as parameters, and assigning an initial value to each zone. The method then adjusts the hydraulic conductivity and recharge values while attempting to minimize the error between calculated and observed heads and flows [18],[19].

The conceptual model approach utilized in this study is particularly suited for this method, as it comprises recharge and hydraulic conductivity regions defined by polygons. Each polygon is designated as a parameter region by assigning a 'key value' that is not expected to appear elsewhere in the MODFLOW input file; typically, a negative value is effective [18],[19].

The model employs six parameter regions, consisting of two hydraulic conductivity regions and four recharge regions. A total of eight observations are used, including seven observation wells and one stream flow value. It is important to note that when using parameter regions, the number of estimated parameters should always be less than the number of observations.

In the hydraulic conductivity regions, values of '-30' and '-60' were entered, while the recharge regions were assigned values of '-1', '-2', '-3', and '-4'. The use of negative values ensures that these regions will be automatically recognized during the calibration phase.

As a result of the PEST calibration, the model identified the most appropriate values. Specifically, PEST determined the recharge regions to be 0.0012, the hydraulic conductivity value for the river region to be 50, and the hydraulic conductivity value for other regions to be 28.85 (Figure 10).

Name	Key	Type	Value	Min	Max
HK_30	-30	HK	28.851103	0.7	50.0
HK_60	-60	HK	50.0	0.7	50.0
RCH_1	-1	RCH	0.0012	0.000095	0.0012
RCH_4	-4	RCH	0.0012	0.000095	0.0012
RCH_2	-2	RCH	0.0012	0.000095	0.0012
RCH_3	-3	RCH	0.0012	0.000095	0.0012

Figure 10. Optimized hydraulic conductivity and recharge values obtained from PEST calibration.

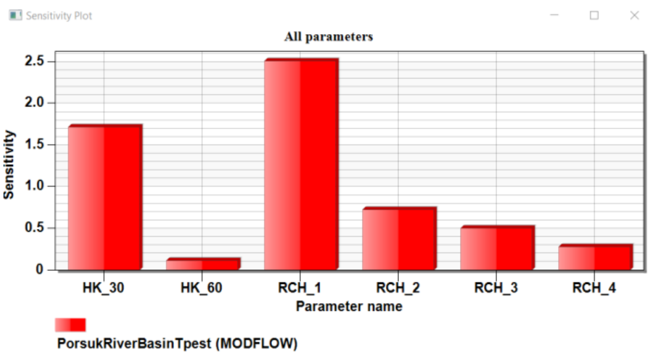

Figure 11. PEST parameter sensitivities plot diagram.

In addition to calculating optimal parameter values, PEST also evaluates the sensitivity of each parameter. This information can be visually represented through a graph created using the drawing wizard in the GMS software (Figure 11).

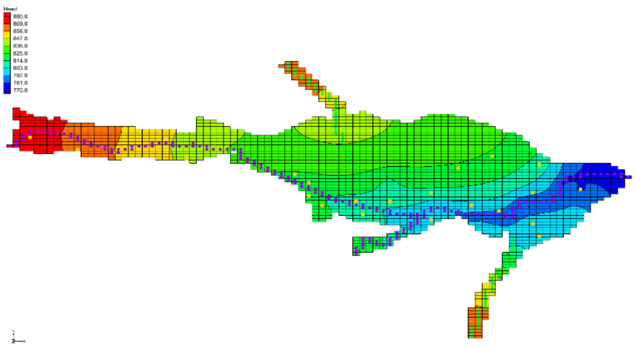

Figure 12. Modeling result after steady-state PEST calibration.

B. *Transition from steady state to groundwater flow modelling*

Simulating subsurface flow often requires the management of large amounts of temporal data from various sources, including pump well data, recharge-discharge information, and water levels in rivers and observation wells. Collecting and formatting such data can be challenging and time-consuming. GMS offers tools to import time series data and convert it into inputs for MODFLOW models [26].

When entering time values associated with transient data, MODFLOW necessitates that time be specified as scalar values relative to a zero-time reference at the beginning of the simulation. Furthermore, the durations must align with the time unit selected for the model. This process can be labor-intensive, as temporary data must be converted from a date/time format to a relative time format [26].

The strategy employed in GMS to manage temporal data allows users to enter all time values using a straightforward date/time format. Temporary data is incorporated into the conceptual model using date/time values, with the time at the beginning of the first MODFLOW stress period serving as the reference point, corresponding to "time=0.0" in the simulation [26].

When the model transitions from a conceptual to a grid model, time values in the conceptual model are automatically mapped to the appropriate time values corresponding to MODFLOW stress periods. Upon saving the MODFLOW model, date/time values are converted to the corresponding relative time values [26].

In addition to enhancing usability, another advantage of the temporal data strategy in GMS is that both spatial and temporal components of the conceptual model are defined independently of the discretization used for grid spacing and stress period dimensions. The stress period range can be modified, and the model can be rebuilt from the conceptual model in a matter of seconds [27].

***Model application*:** First, it is essential to assign the transient recharge rates for the recharge zones. These rates were entered into the zones based on time, drawing on values derived from steady-state calibration and those obtained through the PEST method. The model was then calibrated using data from the observation wells and flow measurements. Five recharge regions are defined by five polygons, with the recharge rate for Zone 1 set to zero, while the other four zones are assigned specific transient recharge rates.

The simulation will incorporate a transient pumping schedule for the six wells, in addition to transient recharge data. Well data were imported from a text file, as the locations are predefined, making it sufficient to import only the pumping schedule. Details of the pumping wells are summarized in Table 4.

Table 4. Pumping well data [8].

Well name	Date	Time	Flow (Q) (m^3/d)
INONU	1.10.1971	07:00:00	0
INONU	1.08.1972	12:00:00	-259.2
INONU	1.09.1972	15:00:00	-2073.6
INONU	1.10.1972	12:00:00	0
OKLUBALI	1.10.1971	12:00:00	0
OKLUBALI	1.08.1972	08:00:00	-86.4
OKLUBALI	15.08.1972	10:00:00	-86.4
OKLUBALI	1.09.1972	11:00:00	0
SATILMIS	1.10.1971	08:00:00	0
SATILMIS	1.08.1972	09:00:00	-34.56
SATILMIS	15.08.1972	12:00:00	-1036.8
SATILMIS	1.10.1972	12:00:00	0
ESKISEHIR1	1.10.1971	14:00:00	0
ESKISEHIR1	1.01.1972	14:00:00	-1399.68
ESKISEHIR1	1.08.1972	07:00:00	-1555.2
ESKISEHIR1	1.11.1972	12:00:00	-1123.2
ESKISEHIR1	1.02.1972	09:00:00	-1123.2
ESKISEHIR1	1.04.1972	12:00:00	0
ESKISEHIR2	1.10.1971	12:00:00	0
ESKISEHIR2	1.08.1972	14:00:00	-1036.8
ESKISEHIR2	1.04.1972	14:00:00	-1741.824
ESKISEHIR2	1.07.1972	07:00:00	-1468.8
ESKISEHIR3	1.10.1971	07:00:00	0
ESKISEHIR3	1.01.1972	12:00:00	-950.4
ESKISEHIR3	1.11.1972	12:00:00	-432
ESKISEHIR3	1.12.1972	14:00:00	0

A storage coefficient must be assigned to the aquifer. Given that the study is conducted in a single layer, a specific efficiency must be designated for the unconfined aquifer.

Unlike steady-state conditions, river analyses require different considerations. Necessary values are assigned to the flow drawn as a constant-level arc. Two river branches converge to form the Porsuk Stream. Due to the system's automatic detection of this confluence, it is sufficient to enter the flow rates for only the two rivers.

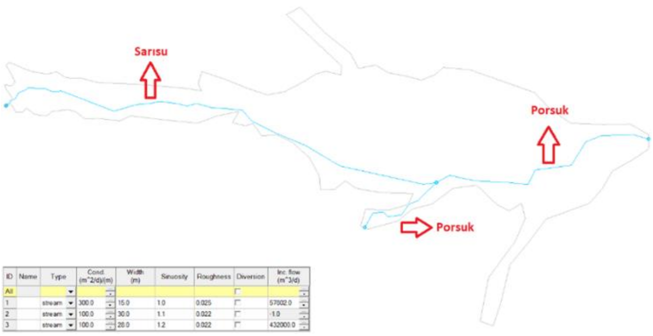

Figure 13. Streaming data

Stress period: MODFLOW discretizes time using stress periods and time steps. Each stress period is associated with a specific duration, during which boundary conditions (or stresses) may change at the beginning of the period. It is necessary to adjust the stress periods before transforming the conceptual model [28].

The modeling of groundwater flow is conducted over the period from October 1, 1971, to September 30, 1972, with this timeframe divided into two segments for each date. The start and end dates, the number of stress periods, and the time interval values must align with the dates and types of data input into the model.

Model:

- 1st Period: This period simulates the lowering of the water table due to water withdrawal from wells while groundwater flow continues [29].
- 2nd Period: This period models groundwater flow once water withdrawal from the wells ceases, resulting in an upward rise of the water table [29].

Model calibration: A new scope designated as "observation" has been defined in the model. An observation point was accurately established in accordance with the model's base, and the observed water table heights were recorded as observation data at this location, following the time series format. The changes in water table elevation observed over time were entered into the system, aligned with the model's stress periods [30].

Transition from steady state to underground flow model and modeling results: After executing the model, a diagram was generated to illustrate the changes in simulated groundwater flow over time, aligned with the stress periods, and to assess its compatibility with the observation data incorporated into the model (Figure 14).

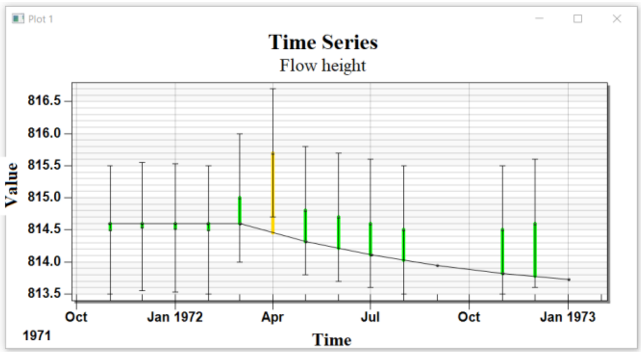

Figure 14. Flow height – time series.

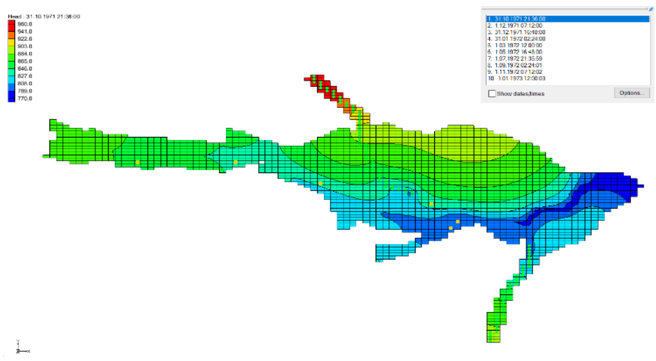

Figure 15. Groundwater flow model results.

DISCUSSIONS

The groundwater flow modeling conducted in the Porsuk Basin using the MODFLOW method provides critical insights into the aquifer dynamics and water resource management in Eskisehir Province, Turkey. This study's dual-phase approach—steady-state and transient flow modeling—enables a comprehensive understanding of the groundwater system, essential for sustainable water resource management.

The calibration process, involving both manual adjustments and the use of PEST software, confirms the reliability of the model. The calculated residual values—Mean Residual, Mean Absolute Residual, and Root Mean Squared Residual (RMSR)—fall within acceptable error margins, indicating a robust alignment between observed and modeled data. This validation is crucial for ensuring that the model accurately reflects the real-world conditions of the aquifer, which is essential for making informed decisions regarding groundwater management.

The findings reveal significant changes in groundwater levels, with an approximate decrease of 1 m/year observed during the 1971 water year. This decline underscores the importance of monitoring groundwater levels over time, particularly in regions reliant on aquifer systems for water supply. The flow budget analysis, which details inflows and outflows from the aquifer, offers a clear depiction of the hydrological dynamics at play. Understanding these dynamics is vital for assessing the sustainability of water extraction and the potential impacts of climate variability and human activities on groundwater resources.

The visual representation of the groundwater flow, with distinct regions indicating surface interactions and deeper groundwater locations, enhances the interpretability of the model results. This spatial visualization aids stakeholders in identifying areas of recharge and discharge, facilitating targeted management strategies. Furthermore, the model's ability to present detailed flow information for selected cells allows for localized analysis, which can inform specific management interventions tailored to different areas within the basin.

One of the most significant advantages of this modeling study is the ease of data integration, which allows for the continuous update of the model. As new hydrological data becomes available, the model can be adjusted to reflect current conditions, ensuring that it remains a relevant tool for ongoing groundwater management. This adaptability is particularly important in the context of changing environmental conditions, such as those resulting from climate change or shifts in land use practices.

In conclusion, the groundwater flow modeling in the Porsuk Basin serves as a valuable resource for understanding and managing the aquifer system. The integration of accurate calibration, flow budgeting, and user-friendly data visualization collectively contribute to a comprehensive framework for sustainable groundwater management. Future research should focus on long-term monitoring and incorporating climate projections into the model to enhance its predictive capabilities and resilience against potential water scarcity issues.

CONCLUSIONS

Groundwater flow modeling was conducted using the MODFLOW method in the aquifer of the Porsuk Basin, located in Eskisehir Province, Turkey. The modeling was approached in two phases: steady state and transient flow.

In the steady-state phase, the model was developed in general terms, boundaries were defined, and calibration studies (both manual and using PEST) were performed to ensure the hydraulic and hydrological values were sufficiently accurate. The 'Mean Residual,' 'Mean Absolute Residual,' and 'Root Mean Squared Residual (RMSR)' values, which indicate the agreement between observed values and those calculated through modeling, were calculated. It was found that the model operated within an acceptable error range (Table 5).

Table 5. Values obtained because of calibration studies.

Measure	Value
Mean Residual (Head)	1.45
Mean Absolute Residual (Head)	1.45
Root Mean Squared Residual (Head)	1.49

In the steady-state model, the configuration established after the calibration studies was accepted as the initial model for simulating flow conditions. Based on the stress periods determined in accordance with the modeling study, changes in groundwater levels and the total flow budget for the 1971 water year were calculated. It was observed that the change in groundwater level during the 1971 water year was approximately 1 m/year.

As a result of the groundwater modeling, a flow budget encompassing all cells within the grids defined in the study area was generated (Figure 16).

	Flow In	Flow Out
Sources/Sinks		
CONSTANT HEAD	77,388.752399445	-580,488.7658234
WELLS	0.0	-28,468.79997253
DRAINS	0.0	-52,145.04681396
RECHARGE	457,027.65603638	0.0
STREAM LEAKAGE	127,670.84008789	-961.6852416992
Total Source/Sink	**662,087.24852371**	**-662,064.2978516**
Zone Flow		
FLOW RIGHT FACE	0.0	0.0
FLOW FRONT FACE	0.0	0.0
FLOW LEFT FACE	0.0	0.0
FLOW BACK FACE	0.0	0.0
Total Zone Flow	**0.0**	**0.0**
TOTAL FLOW	**662,087.24852371**	**-662,064.2978516**
Summary	**In - Out**	**% difference**
Sources/Sinks	**22.950672149658**	**0.0034664721289**
Cell To Cell	**0.0**	**0.0**
Total	**22.950672149658**	**0.0034664721289**

Figure 16. Water budget

In the flow budget, the flows entering and exiting the aquifer from source and recharge points, the volume of water extracted from existing wells, and the amount of recharge are clearly indicated.

The modeling analysis reveals distinct regions within the program interface, with some areas displayed in blue and others in red. The blue regions signify that groundwater is reaching the surface, while the red areas indicate that groundwater is located below the bottom layer defined in the program. Additionally, it is possible to visualize underground water levels.

When a specific cell in the model is selected, information regarding the amount of flow into or out of that cell can be obtained. If multiple cells are selected as a group, the water budget for the selected region is presented in a tabular format. The CCF file generated by the GMS program post-analysis provides further details on the calculation of flow rates between the aquifer and external source and recharge points. Another significant advantage of this study is the ease with which new data can be integrated into the model, allowing for continuous updates. This capability ensures that the model can provide ongoing, accurate information.

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