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EVALUATING GROUNDWATER–SURFACE WATER INTERACTIONS USING AN INTEGRATED HYDROLOGICAL MODEL IN THE PALAS BASIN

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Abstract. Evaluating surface water–groundwater interactions is important for the integrated management of water resources. In this study, SWAT-MODFLOW model, which integrates surface and groundwater models SWAT and MODFLOW, was used to simulate the surface water and groundwater system in the Palas Basin, Türkiye. Palas Basin is a closed-basin located in the semi-arid central region of Türkiye. The basin hosts a playa lake, called Tuzla Lake. The basin is an agricultural basin and both surface water and groundwater are used for meeting irrigation water requirements. Groundwater is also used for municipal water supply and contributes to the sustainability of Tuzla Lake by providing inflow. The SWAT-MODFLOW model for the Palas Basin was calibrated and validated using the streamflow observations in the watershed available for the 2000-2005 period and the groundwater level observations in the monitoring wells from 2016 to 2017. The model provided satisfactory performance for streamflow simulation with coefficient of determination (R^2) and Nash-Sutcliffe efficiency coefficient (NSE) of 0.61 and 0.54, respectively, during the calibration period, and 0.32 and 0.31 during the validation period. The water table fitting results provided the R^2 value of 0.86. The water budget analysis demonstrates that the groundwater recharge was about 7 million m^3/yr. GW abstraction was estimated as 3.5 million m^3/yr and recharge to surface water was estimated as 3.5 million m^3/yr. Increasing groundwater abstraction for irrigation purposes reduces groundwater inflow to Tuzla Lake. The model could be used for simulating surface water-groundwater interactions under changing climatic conditions and groundwater abstraction scenarios in the future.
Keywords: Surface water-groundwater interactions, modeling, SWAT-MODFLOW, Palas Basin, Tuzla Lake

1 INTRODUCTION

Studying the interactions of surface water and groundwater is critical for understanding the hydrological processes in a watershed. Until more recently, many research studies focused on either surface water or groundwater and the link between these systems were only weakly established. Both resources are extensively used for human activities and they are under the threat of overexploitation. Their interactions are, therefore, critical for integrated water management at the watershed scale.

Different methods can be used for examining the linkage between surface water and groundwater, which can be classified as field or experimental methods, analytical modelling approaches, numerical modelling approaches or semi-analytical methods (Banerjee and Ganguly, 2023). Among these methods, numerical modelling approaches have been successfully applied for both hydrological and hydrogeological modelling purposes. Hydrological models aim to develop tools for representation of the surface water system. Hydrogeological models represent the hydrogeological system and the water flow in the porous environment. More recently, some models that integrates hydrological and hydrogeological systems have also appeared (e.g. SWAT-MODFLOW, GSFLOW, MIKE SHE, and HydroGeoSphere) (Ntona et al., 2022). A review of the previous literature shows that the SWAT-MODFLOW model, which integrates Soil and Water Assessment Tool (SWAT) and modular finite-difference flow model (MODFLOW), is listed among the most frequently used software for examining surface water-groundwater relationships (Ntona et al., 2022).

SWAT-MODFLOW model have been applied in different watersheds over the world. To example a few, Surinaidu et al. (2016) used the modelling approach for examining the possibility of subsurface storage in the Ganges River Basin in India. Huo et al. (2016) used an integrated SWAT-MODFLOW model to examine water balance components in the Heihe River in China. Guevara-Ochoa et al. (2020) used it for estimating surface water-groundwater interactions under climate change in the Del Azul Basin in Argentina. Semiromi and Koch (2019) used this apprach for modelling Gharehsoo River Basin, Iran. Literature review shows that the studies that used SWAT-MODFLOW have become more available since 2016. However, most of these studies were conducted in the regions where sufficient data were available for characterization of the surface water and groundwater systems. More research is needed for evaluating the applicability of the SWAT-MODFLOW model under data-scarce conditions.

This study aims to examine the surface water and groundwater exchange in the Palas Basin (Kayseri, Türkiye) (Figure 1) by using the SWAT-MODFLOW platform. The models were both calibrated and validated and used for understanding the effects of water management scenarios. Palas Basin is a semi-arid basin, which have very scarce data about hydrological and hydrogeological characteristics. Therefore, this study can provide insights in application of SWAT-MODFLOW model under data-scarce conditions.

2 METHODS

In this study, the interactions between surface water and groundwater were examined by developing a model using the SWAT-MODFLOW platform. Below, the general characteristics of the Palas Basin were explained and background information about the SWAT, MODFLOW, and SWAT-MODFLOW models was provided. Details about model development process including input data characteristics and sources and model calibration and validation techniques were also presented.

2.1 Site description

Palas Basin (Figure 1) covers an area of 480 km^2 (Azgin and Dadaser-Celik, 2015). It is a closed basin where continental climatic characteristics are observed. The annual average temperature was 10.6^{o}C in the basin based on data obtained from the 1975-2018 period. Annual precipitation changed from 258 mm to 611 mm with an average of 411 mm during this time period. Agriculture is the dominant land use type with 60% coverage. The remaining part of the basin is occupied by sparse vegetation cover (35%) and marshes/lakes (5%). Tuzla Lake and Değirmen River are the major hydrological features in the basin. The topography in the basin is higly variable where the elevations change from 1120 to 2200 m (a.s.l.). In general, the geological formations in the Palas Basin can be examined in three main groups. These are Quaternary alluviums in and around the lake, Tertiary aged formations are seen over a wide area in the east of the basin and Mesozoic aged formations located in a narrow area in the southwest of the basin (Figure 1).

2.2 Background information about the SWAT-MODFLOW platform

SWAT is a watershed-scale hydrology and water quality model that simulates the water budget in the spatial and temporal dimensions (Arnold et al., 1998). SWAT has the potential to be used to assess the effects of long-term hydrological changes and land management practices, especially in agricultural watersheds. Many previous studies have used SWAT to simulate hydrological processes and changes in water quality and quantity resulting from land use and climate changes (Aouissi et al., 2014; Molina-Navarro et al., 2016, Mehdi et al., 2015, Yen et al., 2015). SWAT divides the watershed first divided into subbasins and then into hydrological response units (HRUs). HRUs are areas that have homogeneous land use, soil, and slope characteristics. Water flows are estimated for each HRU, then they are aggregated to create flow for each subbasin. The flow is routed to the rivers and finally to the basin outlet. SWAT uses a one-dimensional system during groundwater flow and neglects spatial variability in aquifer parameters and regional flow characteristics. Therefore, SWAT cannot represent the spatial variations of groundwater levels and their interactions with surface water, i.e., groundwater discharge and runoff seepage.

In contrast, the groundwater flow simulation model, MODFLOW, solves the groundwater flow partial differential equation for hydraulic head (McDonald and Harbaugh, 1984). MODFLOW have been used extensively over the world for simulating groundwater flow and pollutant transport (Morrissey et al., 2015; Saba et al., 2016) MODFLOW performs calculations based on the grid structure, the size of which is determined by the user. In order to use the model, it is necessary to add the groundwater recharge values for each grid and provide the evapotranspiration losses from each grid to the model.

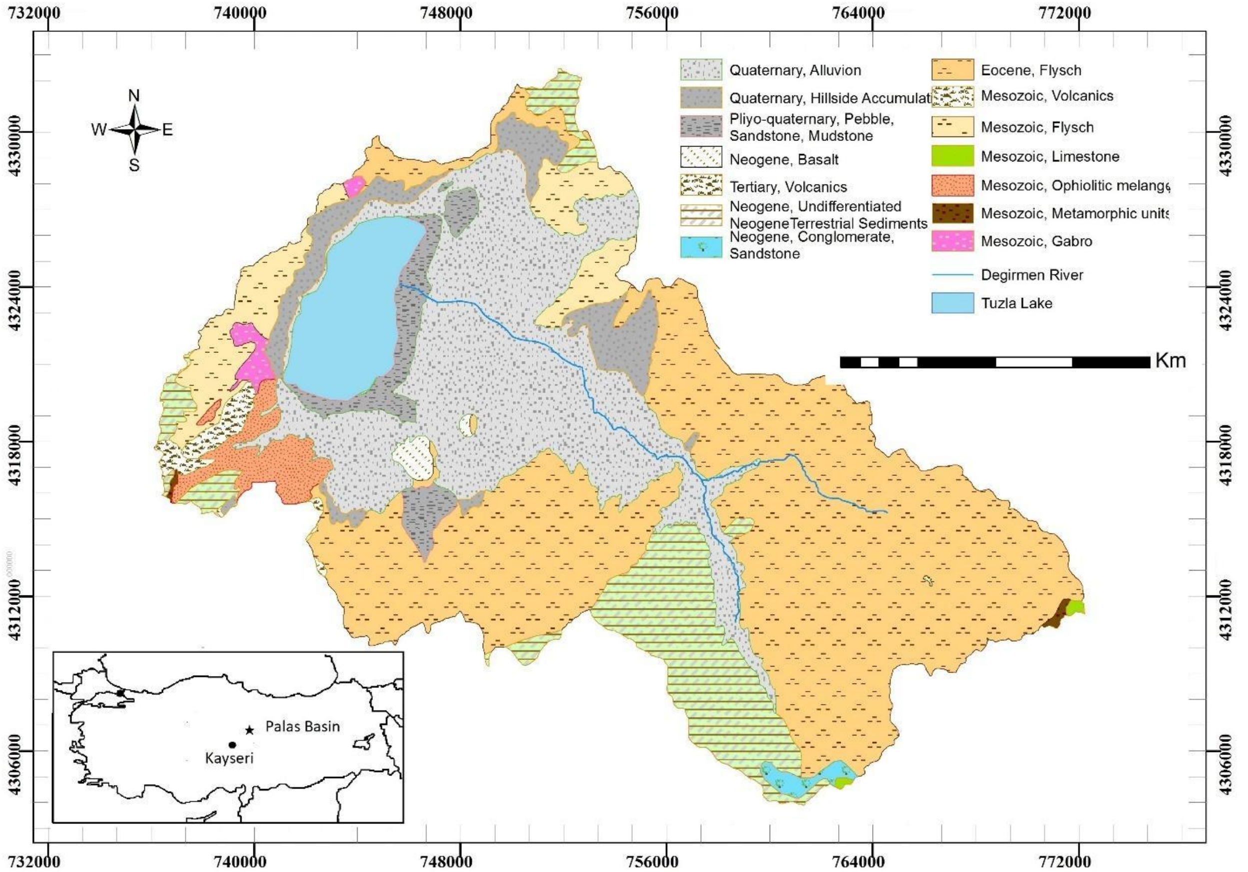

Figure 1. The location and hydrogeological characteristics of the Palas Basin

The weaknesses in both models have been eliminated with the SWAT-MODFLOW platform by integrating SWAT and MODFLOW (Bailey et al., 2016). In the integrated system, precipitation/evaporation, surface flow, subsurface flow, and percolation are simulated by SWAT. MODFLOW simulates surface water-groundwater relationships, groundwater levels, and groundwater flows. The working routine of the SWAT-MODFLOW platform is as follows (Park et al., 2019). First, the infiltration values and evapotranspiration values calculated for each HRU in the basin using the SWAT model are transferred to the MODFLOW grid cells to express groundwater recharge and losses, respectively. In addition, the water depth in the river in the lower basin is transferred to the MODFLOW RIVER cells. The RIVER package in MODFLOW is used to simulate hydraulic conductivity for the riverbed and water transfer between the aquifer and the river network using Darcy's Law. MODFLOW solves the groundwater flow equation and transmits the water table height to each SWAT HRU and return streams to each SWAT subbasin. It is routed to the basin outlet by the flow network of the basin using SWAT's algorithms.

2.2 SWAT model development

The model for Palas Basin was developed with the ArcSWAT interface using SWAT2012 Revision 664 version. Digital elevation model (DEM), soil map, land use-cover map, slope information and meteorological data were used for establishing the model (Figure 2). DEM data was obtained from the United States Geological Survey web site. Land use-cover map for the Palas Basin was obtained from the CORINE 2012 database. The soil map, which includes information about soil types and properties, was acquired from the FAO-UNESCO’s Soil Map of the World. Information on was generated by the SWAT model based on DEM data. Meteorological data included precipitation, maximum temperature, minimum temperature, solar radiation, wind speed, and relative humidity and they were obtained from the Kayseri weather station, located outside the basin. For model calibration and validation, SUFI2 algorithm available in the SWAT-CUP software (Abbaspour, 2015) is used. Model calibration was conducted based on 48 months (2000-2003) of streamflow data from Değirmen Stream. For model validation, 24 months (2004-2005) of streamflow data were used.

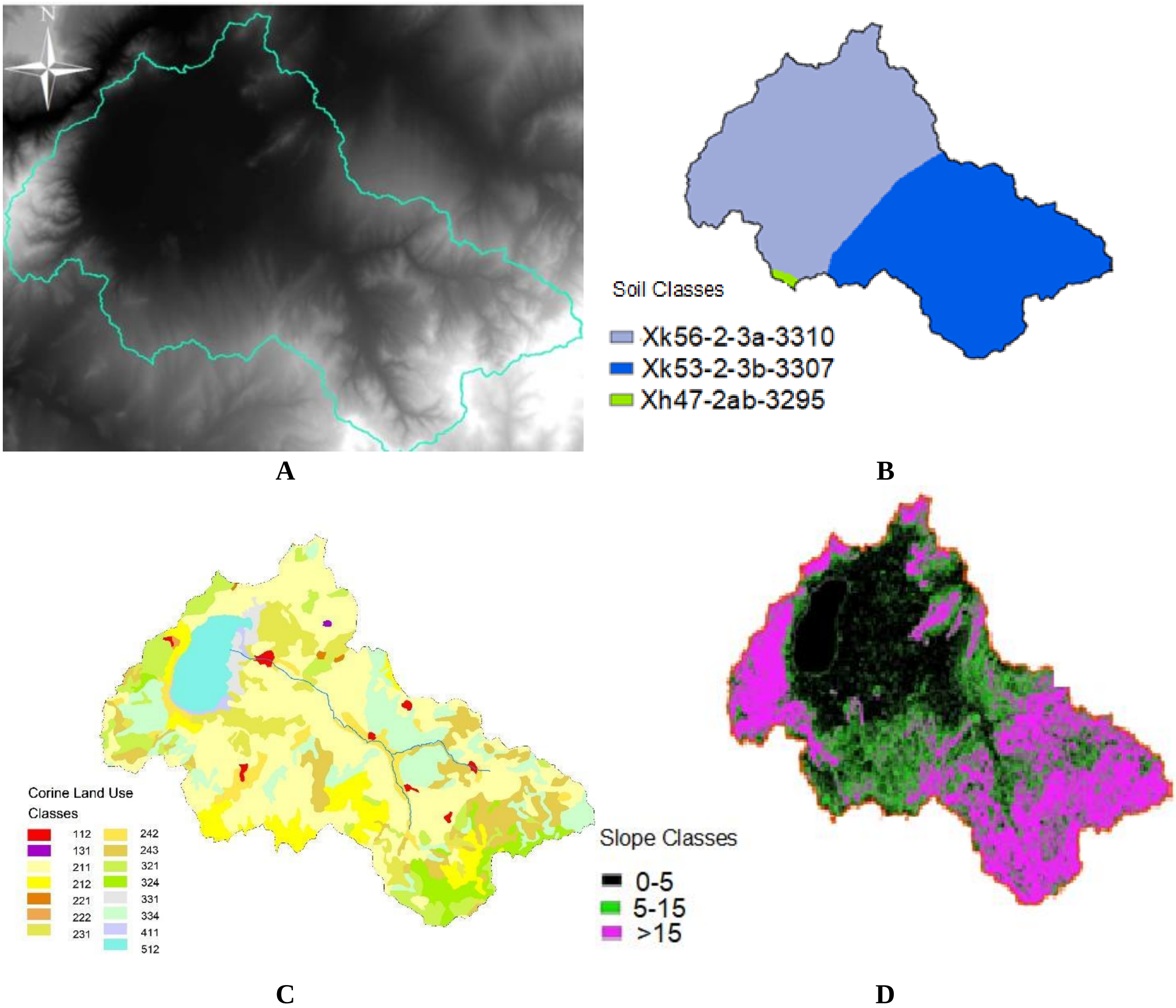

Figure 2. Input data used for the SWAT model. A) digital elevation model B) soil map C) CORINE 2012 land use-cover map D) slope

2.3 MODFLOW model development

The MODFLOW model was created using the FREEWAT platform (De Filippis et al., 2020). The active domain was selected as the alluvial unit located in the center of Palas Basin. The basin area is defined by square grids consisting of 104 rows and 101 columns. The size of the grids was determined as 210 m in the x and y directions. In this way, each grid covers an area of 0.0441 km^2.

The groundwater flow equation is solved for the aquifer system defined as the active cells in the model. Inactive cells (defined as no-flow) were not included in the groundwater flow equation and were not involved in any mathematical operation. When the passive cells in the model are ignored, the remaining active cells are 3808. In Figure 3, active cells are shown in green and passive cells in white. In the mathematical model, the groundwater system was conceptualized as a single layer with a depth of 50 m. Tuzla Lake is modeled with a constant head boundary condition (CHD). The elevation of Tuzla Lake is accepted as 1130 m. Değirmen Stream located in the basin is represented with the river boundary condition (RIVER). Groundwater recharge takes place from precipitation. It has been added to the model with the recharge module (RECHARGE). An important factor in groundwater discharge is extraction from wells. The amount of water allocated for the wells was supplied from State Hydraulic Works. The total abstraction value corresponding to each cell was added to the model using the WELL module. The model was first run on an annual time scale and under steady-state conditions. The model was calibrated using the average water levels of 27 wells previously collected in the basin.

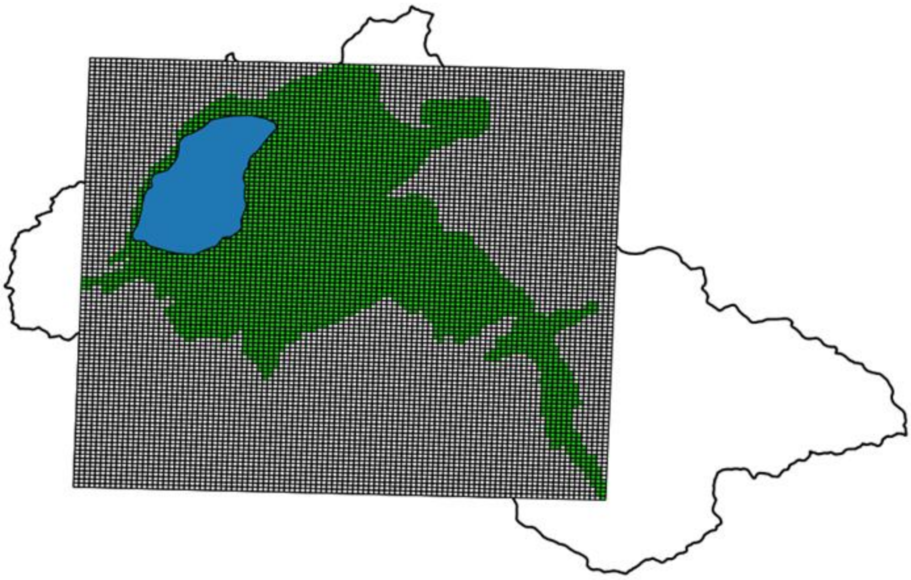

Figure 3. MODFLOW grids

2.4 SWAT–MODFLOW Integration

The most important problem in the integration of SWAT and MODFLOW is that both models have different spatial resolutions. HRUs are the spatial units in SWAT. In MODFLOW, spatial discretization is based on grids. At the SWAT-MODFLOW platform, each HRU in SWAT is intersected with MODFLOW grid cells for create a common spatial unit for two systems. First, the HRUs are separated into individual polygons. These polygons are used to transmit HRU-based values to MODFLOW grid cells based on the percentage of DHRU (decoupled HRUs) area contributing to the grid cell area. DHRUs keep the same variable information with the original calculation of HRUs. MODFLOW RIVER cells that define the catchment stream network is connected with SWAT river network. For SWAT and MODFLOW to work together, HRUs should be connected to DHRUs (File 1), DHRUs should be connected to MODFLOW grid cells (File 2), MODFLOW grid cells should be connected to DHRUs (File 3), and SWAT subbasin river cells should be connected to grid cells (File 4) Four SWAT-MODFLOW input files are required to keep mapping information. SWAT-MODFLOW reads the information in the text files at the beginning of the simulation and provides the necessary conversions between MODFLOW and SWAT.

3 RESULTS AND DISCUSSIONS

3.1 The performance of the SWAT model

The SWAT model consisted of 23 subbasins and 408 HRUs. In general, the simulated and observed values in model calibration and validation are compatible with each other. In the model calibration, the Nash-Sutcliffe Efficiency (NSE) value was calculated as 0.61 and the R^2 value was calculated as 0.54. During the validation period, NSE and R^2 were 0.32 and 0.31, respectively. The results obtained with the SWAT model are shown in Figure 4 for the period 2000-2005. The simulated and observed streamflow values are compatible with each other except for a few extreme points. However, in some years, especially during the validation period, the magnitude of the peaks could not be adequately simulated.

The performance of the SWAT model in Palas Basin could be affected by a variety of factors. In this study, the uncertainties in the input data and data used for calibration/validation can be listed among the most important factors that reduce the model performance. The low temporal and spatial resolution of the input data can also be evaluated in this context. For example, soil data set was obtained from the FAO/UNESCO map in Palas Basin, which may not adequately reflect the actual soil conditions for a small basin, such as Palas Basin. However, this soil data was the only available data that can be input to SWAT without additional field studies. Another issue for Palas Basin was that there is no meteorological observation station in the basin until 2021 and there are also missing records in the meteorological data obtained from the Kayseri meteorological station used in the model. This may have prevented the representation of some local-level climatic events (Abbaspour et al., 2007). Finally, the differences between the period in which the model is calibrated and the validation can affect model performance (EPA., 2002). Changes occur in water management and land use over the years.

It was not possible to adequately reflect this variability in the model. In addition, data for the period 1997-2005 were used to calibrate and validate the model, since data for the more recent period were not available. This situation also created difficulties in the flow estimations. Despite this, the model generally produced successful results in seasonal and annual flow simulation.

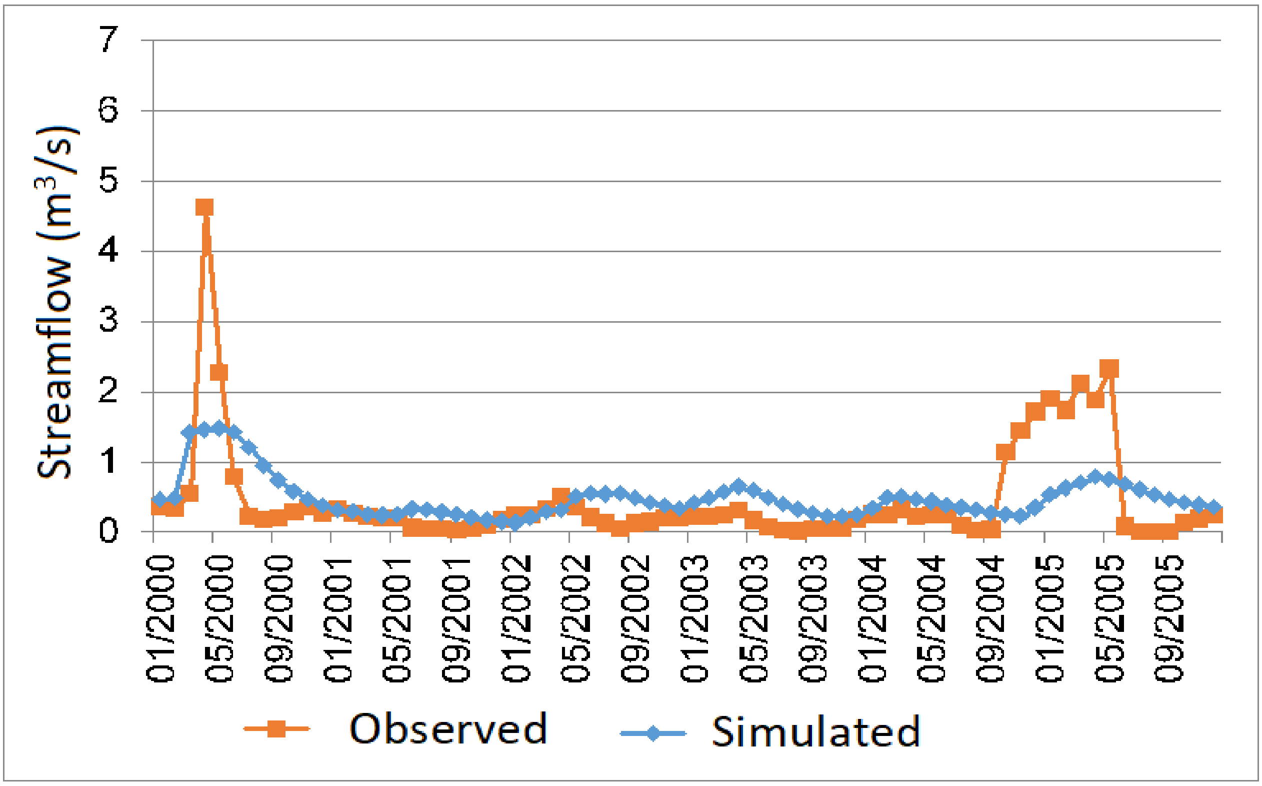

Figure 4. Simulated and observed streamflow in the Palas Basin

The annual average precipitation for the Palas Basin for the 1990-2020 period was calculated as 325.7 mm based on model simulations and the annual potential evapotranspiration was estimated as 926.2 mm. The actual evapotranspiration was 281.7 mm. Groundwater recharge rates vary spatially in the basin, but the average annual seepage into the aquifer was estimated at 21 million m^3. Approximately 16 million m^3 of groundwater recharge was lost due to evapotranspiration on the annual time scale. Annual net 6 million m^3/year of this flow reaches groundwater. The ratio of the infiltration to precipitation was calculated as 0.14.

3.2 The performance of the MODFLOW model

The MODFLOW model was manually calibrated using the level data of 27 wells collected during the 2016-2017 period. After calibration, the simulated and observed values were generally compatible (Figure 5). The R^2 value calculated between the observed and simulated values was 0.86.

Relatively low agreement between the groundwater model results and the observed values at some points can be due to the uncertainties in the input data and the deficiencies in the data used in the calibration. In this study, the system is conceptualized in its simplest form. In particular, the spatial changes that may exist in aquifer properties were not included in the model. At the same time, the water withdrawal values from the wells, which are the most important component of groundwater discharge, were estimated based on the water allocations given by the State Hydraulic Works. Although the amounts of groundwater allocated to different users in the basin were provided, it was determined that much different amounts of water were used during the field studies. In addition, the amount water use was extremely variable throughout the year and among years. The lack of detailed information on groundwater abstraction rates prevented this variability from being included in the model.

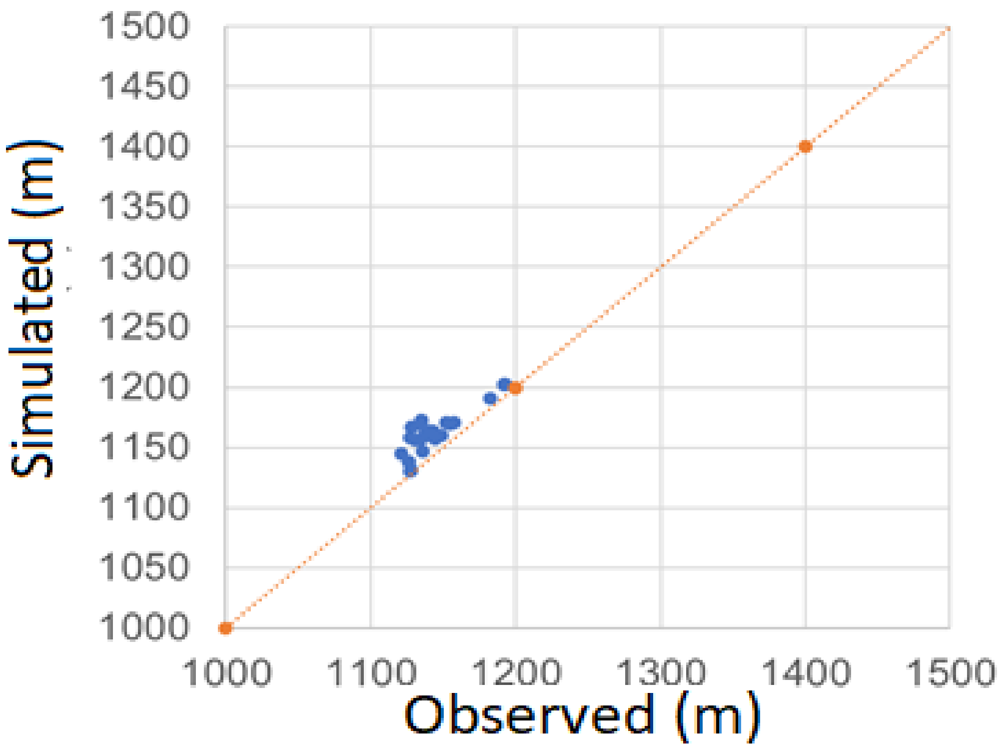

Figure 5. Simulated and observed groundwater levels in the Palas Basin

By running the model, steady state water levels were estimated. Under stable conditions, the system is mainly fed by precipitation. Recharge from precipitation was estimated as 6.8 million m^3. In addition, there is leakage from the river (0.05 million m^3) and recharge from the fixed load (0.6 million m^3), but this amount is extremely low. Groundwater discharge is in the form of withdrawal from the wells (3.5 million m^3) and leakage into the river (1.8 million m^3) and leakage towards the constant head (Tuzla Lake) (1.6 million m^3).

3.3 Simulations with SWAT-MODFLOW

The effects of increase and decrease in groundwater abstraction rates were simulated with the models. In this context, the amount of water withdrawn from the wells was increased by 10% and decreased by 10%. The increase in the use of groundwater significantly reduces the water levels, particularly in the region located in the southeast of Tuzla Lake, where the wells are densely located. However, if the water withdrawal from the wells is reduced by 10%, there is an increase in groundwater levels throughout the basin, including in the same region. The effect of the changes in the withdrawal from the wells on the amount of groundwater discharged into Tuzla Lake and Değirmen Stream was also evaluated. The discharge into Tuzla Lake, which is 1.6 million m^3/year in the base scenario, decreases to 1.5 million m^3/year when the extraction from the wells increases by 10%. When the withdrawal from the wells is reduced by 10%, the amount of groundwater reaching Tuzla Lake increases to 1.7 million m^3/year.

4 CONCLUSIONS

This study focused on the interactions between groundwater-surface water systems in the Palas Basin. For this purpose, a surface water model developed with SWAT and a groundwater model developed with MODFLOW were integrated for Palas Basin on the SWAT-MODFLOW platform. The developed models were calibrated using the data collected in the basin in the past years.

Model performances with both SWAT and MODFLOW fell slightly behind the expected values. This may be originated from limitation such as deficiencies and uncertainties in the input data, problems in the data used in model calibration/validation, and problems with conceptualizing the current state of the watershed. However, surface and groundwater interactions were simulated in a basin like Palas Basin where historical data is extremely limited. The effects of different scenarios were evaluated with the models. In general, it was observed that decreases that may occur in groundwater recharge and increases that may occur in groundwater use may cause a decrease in groundwater levels. With the decrease in groundwater levels, the amount of water reaching into Tuzla Lake and Değirmen Stream decrease. This study showed that groundwater levels in the Palas Basin are extremely sensitive to groundwater recharge and withdrawals.

This study showed that the SWAT-MODFLOW model provided reasonable results for analyzing the surface water and groundwater interactions under data scarce conditions. The model developed in this study could be used for simulating surface water-groundwater interactions under changing climatic conditions and groundwater abstraction scenarios in the future.

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