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Modelling surface water-groundwater interactions at the Palas Basin (Turkey) using FREEWAT

Modellazione delle interazioni tra acque suprficiali e acque sotterranee nel bacino di Palas (Turchia) utilizzandoFREEWAT

Filiz Dadaser-Celik, Mete Celik

Riassunto: Il bacino di Palas è un bacino chiuso semiarido situato nella regione turca dell'Anatolia Centrale. La principale attività economica nel bacino è l'agricoltura. Pertanto, sia le acque superficiali che le acque sotterranee sono utilizzate per l'irrigazione. Tuttavia, l'uso intensivo delle risorse idriche minaccia l'equilibrio idrogeologico di un importante sistema lacustre (Lago di Tuzla) situato nel bacino. In questo studio abbiamo analizzato i rapporti tra gli utilizzi idrici agricoli nel bacino di Palas e l'acqua che scorre al lago di Tuzla usando un modello di flusso di acqua sotterranea sviluppato con la piattaforma FREEWAT. La griglia del modello con risoluzione di 250 m x 250 m ha incluso l'intero bacino. Sono state identificate due unità idrostratigrafiche. Gli ingressi verso il sistema sono rappresentati dalla ricarica meteorica, mentre le uscite dall'evapotraspirazione e dagli emungimenti. Il modello è stato eseguito per un anno a condizioni di stabilità. Tre scenari sono stati simulati per comprendere l'effetto dell'utilizzo delle acque sotterranee sull'idrologia del lago. Il primo scenario presupponeva che non vi fosse alcuna estrazione delle acque sotterranee. Il secondo e terzo scenario hanno previsto una variazione dei prelievi idrici del 50% in più o in meno rispetto alle condizioni di riferimento. Il modello ha simulato con successo il flusso ed i carichi idraulici delle acque sotterranee nel bacino. Il volume di ricarica annuale assegnato è stato di 5.27 milioni di m^3. Le uscite dell'acquifero sono dovute al pompaggio (1.49 milioni di m^3/anno), alla perdita del fiume Değirmen (2,25 milioni di m^3/anno) e alla penetrazione del lago di Tuzla (1.53 milioni di m^3/anno). L'alimentazione sotterranea verso il lago di Tuzla è risultata essere significativamente influenzata dai prelievi tramite pozzi. L'aumento dei tassi di pompaggio delle acque sotterranee riduce i flussi delle acque sotterranee al lago di Tuzla e abbassa i livelli di acqua del lago. Questa analisi ha dimostrato che la protezione delle caratteristiche idrologiche del lago di Tuzla è possibile solo con un maggiore controllo sui prelievi di acque sotterranee.

Abstract: *Palas Basin is a semi-arid closed basin located in the Central Anatolia region of Turkey. The major economic activity in the basin is agriculture; therefore, both surface water and groundwater are used for irrigation. However, intensive use of water resources threatens the hydrologic sustainability of an ecologically important lake ecosystem (Tuzla Lake) located in the basin, as it is hydrologically dependent on surface and groundwater flows from the basin. In this study, we analyze the relationships between agricultural water uses in the Palas Basin and water flows in to the Tuzla Lake using groundwater flow model developed with the FREEWAT platform. The model grid with 250 m x 250 m resolution was created based on the entire watershed, where two hydrostratigraphic units were identified. The source terms defined to the model were rainfall recharge and the sink terms were evapotranspiration and groundwater abstraction from wells. The model was run for one year at steady-state conditions. The model successfully simulated the direction of groundwater flow and groundwater levels in the basin. Annual groundwater recharge was simulated as 5.27 million m^3. Groundwater losses were due to pumping (1.49 million m^3/yr), leakance to Değirmen River (2.25 million m^3/yr) and seepage to Tuzla Lake (1.53 million m^3/yr). Three scenarios were simulated to understand the effect of groundwater use on the lake hydrology. The first scenario assumed that there was no groundwater abstraction. As the second and third water management scenarios, the model was run with 50% less and 50% more groundwater abstraction than that of the current conditions. Water flows to Tuzla Lake were significantly related to groundwater abstraction rates. Increasing groundwater pumping rates reduces groundwater flows to Tuzla Lake and lowers lake water level. No groundwater abstraction and reduction in groundwater pumping rates increase water flows to Tuzla Lake and allow higher lake water levels. This analysis showed that protection of hydrologic characteristics of Tuzla Lake is only possible with more control on groundwater abstraction.*

Keywords: *Groundwater/surface-water relations, Groundwater management, Numerical modeling, FREEWAT, Palas Basin (Turkey).*

Parole chiave: Relazioni acque sotterranee/superficiali, gestione delle acque sotterranee, modellazione numerica, FREEWAT, Bacino di Palas (Turchia).

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Introduction

Groundwater depletion is one of the major negative impacts associated with irrigated agriculture. Extensive use of groundwater can cause decreases in groundwater levels, intrusion of saline water at coasts, and reduction of base flow to lakes and wetlands. In this study, the objective was to analyze the interaction between surface water and groundwater in the Palas Basin in Turkey (Fig. 1) to understand the relationships between groundwater abstraction and flows in to a lake ecosystem.

Palas Basin is an agricultural basin that hosts an important lacustrine ecosystem (Tuzla Lake), which collects both surface water and groundwater from the basin. Being in a semi-arid region, water resources are scarce and almost all available surface water and groundwater resources are used for irrigation. However, intensive use of water resources threatens the sustainability of Tuzla Lake ecosystem located in the basin. Tuzla Lake is one of important wetlands in Turkey that has a strong conservation status. It was declared a Nature Conservation Area by the state and under conservation through the Wetland Conservation Regulation of 2002 for its high biodiversity value. However, significant decreases in lake water levels and lake surface area have been observed in recent decades (Azgin and Dadaser-Celik 2015; Cengiz and Dadaser-Celik 2012). During the 1998-2005 period, the rate of groundwater level decline was as high as 6.7 cm/year (Cengiz and Dadaser-Celik 2012). However, only a few studies have been conducted to determine causes of these changes, their consequences, and how they can be prevented. The relationships between surface water flows and groundwater levels were examined very recently (Azgin and Dadaser-Celik 2015, Amiri et al. 2017), but the linkage between lake levels and groundwater levels is still unexplored. The farmers in the basin have continuing demands for new wells; therefore an increase in groundwater use is expected in the future. There is an urgent need to develop water management policies that can examine the interaction between surface water and groundwater in the Palas Basin.

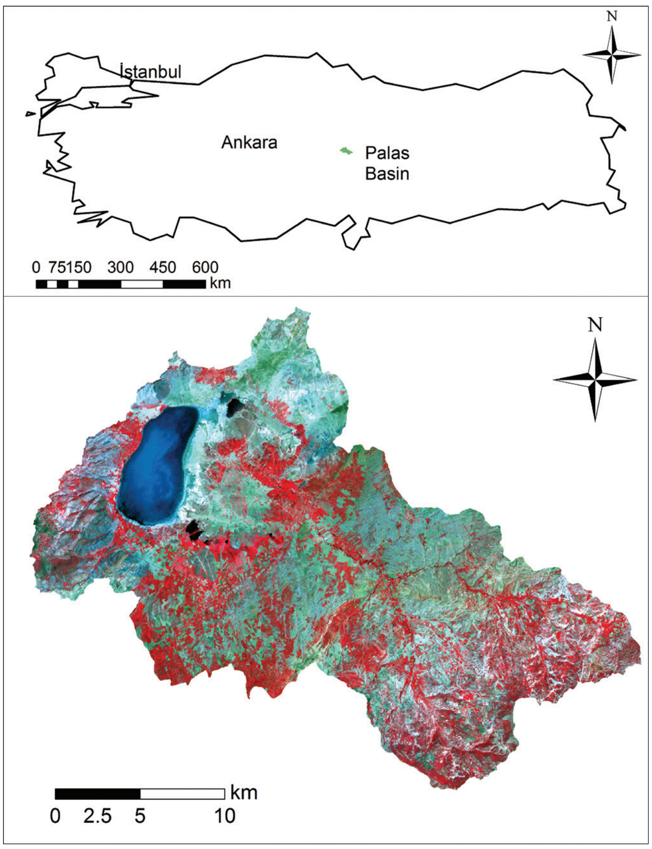

Fig. 1 - Location and geographic characteristics of Palas Basin in Turkey. Palas Basin was shown on a false-color Landsat Thematic Mapper imagery.

Fig. 1 - Inquadramento e caratteristiche geografiche del bacino di Palas in Turchia. Il bacino di Palas Basin è mostrato con banda a falso colore utilizzando un'immagine satellitare.

In this study, we aimed at understanding the relationships between agricultural water uses in the Palas Basin and surface water and groundwater flows to the Tuzla Lake by using the modeling tools available under FREEWAT platform. FREEWAT is an open source and public domain GIS integrated modeling environment for the simulation of water quantity and quality in surface water and groundwater with an integrated water management and planning module (Rossetto et al. 2015). FREEWAT platform is based on the groundwater model (MODFLOW) and has been integrated as plugin into the open-source GIS program of QGIS. The groundwater flow model developed using FREEWAT was used to explain the susceptibility of the hydrology of Tuzla Lake to the groundwater abstraction.

Site Description

Palas Basin is a semi-arid closed basin with a drainage area of about 480 km^2 (Azgin and Dadaser-Celik 2015). The climate in the Palas Basin is characterized by the continental climate with hot and dry summers and wet and cold winters. The annual average temperature during the 1987-2011 period was 10°C (±1°C standard deviation). During the same time period, annual total precipitation ranged from 258 mm to 614 mm with an average of 412 mm (±91 mm standard deviation) (Azgin and Dadaser-Celik 2015). Agricultural areas cover about 60% of the basin. The remaining areas consist of sparse vegetated cover (35%) and lakes and marshes (5%) (Azgin and Dadaser-Celik 2015).

The landform has a typical plain landscape and the elevation ranges approximately from 1120 to 2200 m above sea level (a.s.l.) (Figure 2). Topography inclines form east to west, towards the Tuzla Lake. There is a sedimentary plain in the eastern part and an alluvial plain in the central part. The soil type is dominated by clay loam and loam according to Harmonized World Soil Database (FAO/IIASA/ISRIC/ISS-CAS/JRC 2009).

The Palas Basin is surrounded by mountainous and hilly areas. The basin was formed by the filling of the basin in the quartz-rich alluviums. The mountains surrounding the western part of basin consist marly, greyish and calcareous

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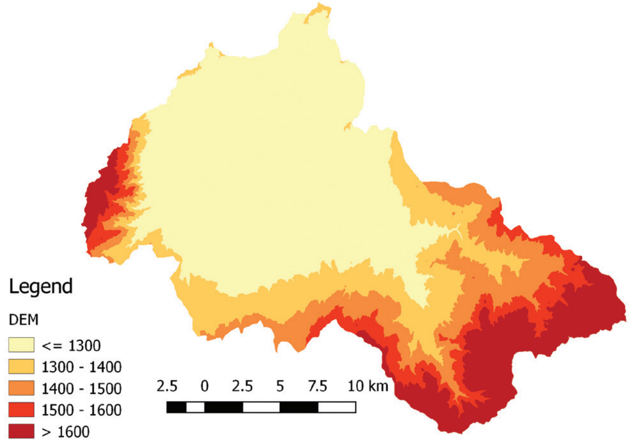

Fig. 2 - Digital Elevation Model of the Palas Basin (Values are in meters above sea level).

Fig. 2 - Digital Elevation Model (DEM) del bacino di Palas Basin (i valori sono espressi in metri s.l.m.).

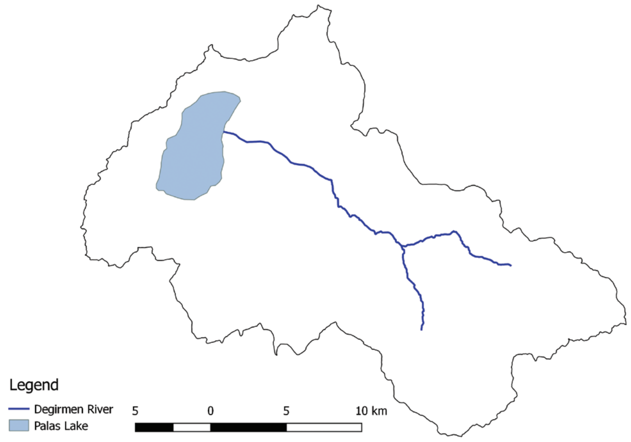

Fig. 3 - Location of Tuzla Lake and Değirmen River at Palas Basin.

Fig. 3 - Localizzazione del lago Tuzla e del fiume Değirmen, all'interno del bacino di Palas.

rocks containing conglomerates in some places. The ophiolites in the southern mountains contain large serpentine blocks which are found in volcanic rocks such as diorite and gabbro. In the southern part, there are gypsiferous formations and the tuffs of Mount Erciyes volcano. The lower eastern and northern parts of the basin are also composed of gypsiferous formations and ophiolites towards the edges. The transport of sediments carried from the mountains in the west developed accumulation zones in the areas where the resulting slope has decreased. In the south there are individual volcanic cones (Somuncu 1999). Groundwater-bearing formations include clay-rich materials (DSI 1970). The recharge of the groundwater occurs mainly through precipitation. The outflows are due to evaporation from Tuzla Lake and upper aquifer layer. The formations around the Tuzla Lake consist of sandy, gravelly, and clayey material and have transmissivity of about 65 m^2/day. In the formations to the east of the basin the transmissivity was 60 m^2/day. Groundwater potential in the basin very low and the safe groundwater yield for the basin was calculated as only 7 million m^3/yr, which was estimated 70% of annual average recharge (DSI 1970). In this calculation, water requirement of Tuzla Lake was not considered.

Major hydrological features in the Palas Basin are Tuzla Lake and Değirmen River. Tuzla Lake, which is the second largest salt lake in Turkey, occupies the west of the basin. The average area of the lake is 35 km^2 but lake area changes very much during and between years. Tuzla Lake is fed by precipitation, groundwater flow, and discharge from a small river, called Değirmen River. The river flows from southeast to northwest and ends up in Tuzla Lake (Fig. 3). Tuzla Lake also collects water flows from the nearby southern, western, and northern areas. Average flow rate of Değirmen River is 0.56 m^3/s. There are a number of springs in the basin. The most important is Yertaşın Spring, located to the southeast of Tuzla Lake.

Methods

In this study, a groundwater flow model was developed for Palas Basin using the FREEWAT platform. Below, we first explain the conceptual model and data sources. Then, we provide details about model development including parameter estimation and model calibration. Finally, we explain the water management scenarios used to analyze the surface water and groundwater interaction in the basin.

Conceptual model

Since the Palas Basin is a closed basin, it can be conceptualized as an isolated system in terms of surface water and groundwater (DSI 1970) interaction with the surrounding basin(s). The aquifer system consists of two layers. The upper aquifer consists of gravelly and clayey material and the second aquifer layer consists of clayey and sandy material. Both groundwater and surface flow in the basin eventually discharges into the Tuzla Lake.

In this study, the inflows and outflows of the aquifer system were simulated. Recharge to the upper aquifer occurs through precipitation and leakage from surface runoff (river). Precipitation recharge shows spatial variation and dependent on land use, slope, and soils in the basin. Previously, a surface water flow model was developed using Soil and Water Assessment Tool (SWAT) (Amiri et al. 2017). With this model, average annual recharge to the aquifer was estimated as 21 million m^3 (45 mm) for the 1990-2015 period. About 16 million m^3 (35 mm) of groundwater recharge was estimated to be lost to evapotranspiration (evapotranspiration from the deep aquifer) at the annual scale. Spatial distribution of recharge rates are provided in Fig. 4. The difference between aquifer recharge and aquifer evapotranspiration, which was calculated as 6 million m^3 (9 mm) for the 1990-2015 period, is the net recharge to the deep aquifer system. This groundwater recharge of 45 mm is about 10% annual precipitation, which is reasonable. The outflows from the aquifer is through evapotranspiration, leakage to river, and leakage to Tuzla Lake. For Tuzla Lake, water inflows are from precipitation, surface runoff (overland flow and stream flow) and groundwater. Evaporation is the only outflow from the Tuzla Lake.

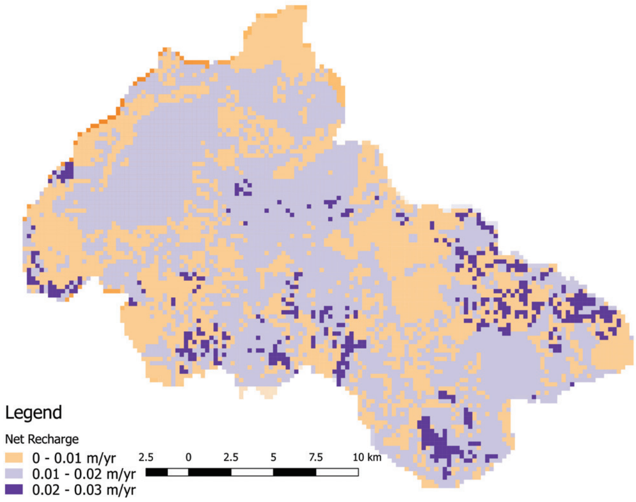

Fig. 4 - Groundwater recharge rates at the Palas Basin.

Fig. 4 - Ricarica della falda che insiste sul bacino di Palas.

Groundwater extraction or pumping is the other process included. The groundwater use is widespread in the western and central parts of basin (Fig. 5). Agricultural areas also present in these regions. The elevation and depth to groundwater increase in the eastern basin, therefore groundwater abstraction is not always feasible. We do not have reliable records on groundwater pumping rates. We assumed that groundwater pumping was about 1.49 million m^3/yr. This value is calculated using the groundwater pumping licenses issued by State Hydraulic Works.

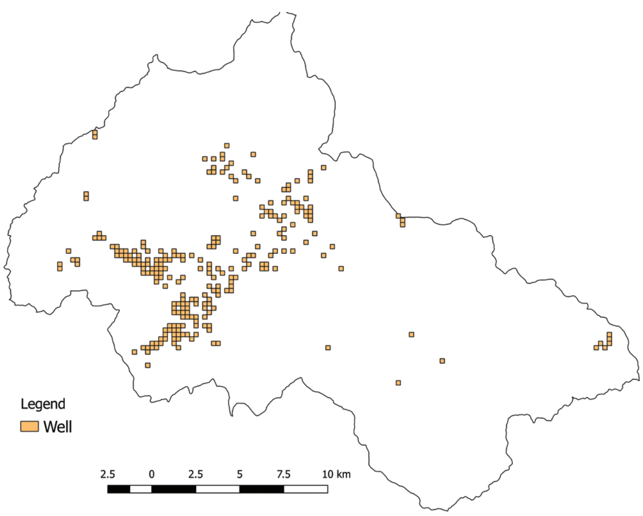

Fig. 5 - Pumping wells in the Palas Basin.

Fig. 5 - Pozzi di estrazione attivi presenti nel bacino di Palas.

Model Development

The active domain was selected as the Palas Basin (Fig. 6). The active domain covers an area of 470 km^2. The model grid is created based on the entire watershed. Grid resolution of 250 m x 250 m was selected. This created a total of 16,416 computing cells. All the grids outside Palas Basin were set to inactive, which resulted in 7526 active cells.

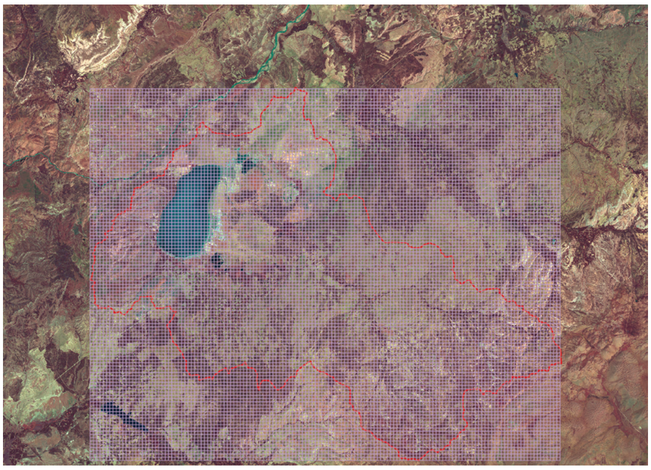

Fig. 6 - Active domain and model grid. The active basin is delineated with the red line.

Fig. 6 - Dominio attivo e griglia del modello. L'area con celle attive è delineata dalla linea rossa.

Vertical discretization was determined based on DEM (digital elevation model), geology, and lake bathymetry. Two hydrostratigraphic units were identified. The upper unit is an alluvial aquifer composed of sandy and clayey material with variable thickness according to topography. The lower unit is an aquifer composed of clay-rich material with thickness of about 100 m. The top layer of the upper aquifer corresponds to the surface elevation of the area discretized using a DEM which has 30 m x 30 m resolution (see Figure 2). The DEM was averaged to 250 m x 250 m. The elevation of the top layer is shown in the Fig. 2 and the bottom elevation of the top layer was set to 1100 m. The lower aquifer depth was set to 1000 m and assumed to be constant through the domain.

We applied no flow boundaries to the northern, southern, eastern, and western sides, since the basin is a closed basin. Tuzla Lake was represented with the Lake (LAK) boundary. 439 cells in the upper aquifer layer were selected as lake cells. Information on lake bathymetry was not available. The bathymetry of the lake was estimated from the DEM, assuming that water depth in the lake was 1 m. Inflows and outflows of the lake were calculated using a water budget approach. To calculate water budget for Tuzla Lake, we used the average values for the 1990-2015 period. During that period, annual precipitation was 402 mm and annual evaporation was 1209 mm. Annual precipitation data were collected at Kayseri Meteorology station, located about 30 km from the Palas Basin. Evaporation data was calculated based on Hargreaves Method using metrological data from the same station. Annual water flows from surface runoff was set to 12 million m^3/yr, which was the average flow for the 1990-2015 period, calculated by the SWAT model (Amiri et al. 2017). The average stage of the lake was set to 1132 m. Minimum elevation was set to 1126 m, maximum elevation was set to 1133 m. The water levels in the lake change continuously through the year and between years. The leakance from the lake bottom was assumed to be 5000 m/yr. The Değirmen River was modelled as River (RIV) boundary. The river bottom elevations were extracted from the DEM. Based on our observations in the Palas Basin, we assumed that the stage of the river is 1 m above river bottom.

The source term defined in the model was rainfall recharge and the sink terms were evapotranspiration and abstraction by wells. Precipitation recharge to the basin was estimated from a surface water flow model developed using SWAT (Amiri et al. 2017). For this period, the deep aquifer recharge was calculated as the difference between recharge and evapotranspiration values, as 9 mm (6 million m^3/yr). Groundwater abstraction in the Palas Basin was simulated with the well package. We had very limited data on groundwater pumping rates. The locations of pumping wells and estimations on annual average pumping estimations were available from State Hydraulic Works. We assumed that groundwater pumping occurs from 245 wells and for each well the pumping rate was assumed to be 6000 m^3/yr (1.49 million m^3/yr total). The model was run under steady-state conditions.

The model solves groundwater flow. Preconditioned Conjugate-Gradient (PCG) was used as numerical solver. HCLOSE (head change criterion for convergence) and RCLOSE (residual criterion for convergence) values were set to 0.1. Outer iteration was set to 200 and the inner iteration was set to 100. For the lake package theta (explicit/implicit solution for lake stages, set to 1 at steady-state simulations), nssitr (Maximum number of iterations for Newton's method of solution), and sscncr (convergence criterion for equilibrium lake stage solution by Newton's method), were set to 1, 99, and 0.01, respectively.

Water Management Scenarios

Three scenarios were run on the model to evaluate the effects of different pumping rates on groundwater input to Tuzla Lake. In the reference condition, groundwater abstraction was 1.49 million m^3/yr.

1. The first scenario was run for determining the conditions without groundwater abstraction in the Palas Basin. The model was run by activating only groundwater recharge. In other words, groundwater abstraction was not simulated.
2. The second scenario was run to understand the effects of decreases in groundwater pumping in the basin. Groundwater abstraction was decreased by 50% to 0.75 million m^3/yr compared to the reference condition.
3. The third scenario was run to understand the effects of increases in groundwater pumping in the basin. Groundwater abstraction was increased by 50% to 2.25 m^3/yr compared to the reference condition.

Results

Below, we first explain model calibration results. Then, results of reference simulation were provided. Finally, we explain the results of water management scenarios and evaluate the results.

Model calibration

Due to limitations of data, only manual calibration of the hydraulic conductivity values was done. The hydraulic conductivity values reported for the Palas Basin was on the order of 30-60 m/yr in the FAO/UNESCO Soil Map of the World. These values provided a starting point for manual calibration. After several trials, Kx and Ky was set to 100 m/yr and Kz was set to 10 m/yr for the upper aquifer. Kx and Ky was set to 30 m/yr and Kz was set to 3 m/yr for the lower aquifer. Ss and Sy values were selected as 0.001 and 0.3, which are typical values for clayey soils.

In general, water budget calculated with the FREEWAT model was close to the water budget calculated in previous studies by DSI (1970). DSI's calculation was based on average conditions and it does not consider groundwater abstraction by pumping wells. DSI developed the water budget for the whole basin and defined evapotranspiration as the only water outflow from the basin. Based on these assumptions, water inflows and outflows to the groundwater systems were estimated as 9.9 and 9.5 million m^3/yr by DSI. Recharge from precipitation (5.88 million m^3/yr) and recharge from surface runoff (2.37 million m^3/yr) were defined as major water inflows to the system by DSI and that constitute about 8 million m^3/yr. Evapotranspiration was assumed to be either from lake or from the upper aquifer and was calculated to be 9.5 million m^3/yr. Also based on estimated evaporatranspiration values, DSI calculated a residual of 1.61 million m^3, which they speculated to be inflow from the surrounding aquifers. The implemented FREEWAT model estimated water inflows and outflows as 5.27 million m^3/yr. One of the major reasons for the difference between recharge values are due to the assumptions made during calculations. DSI assumed that 20% percent of precipitation enters to the aquifer system. Our calculations reflects the average meteorological conditions for the 1990-2015 period and inflows and outflows to the aquifer systems were extracted from a calibrated and validated surface water flow model (SWAT). Annual evapotranspiration losses from Tuzla Lake were estimated as 3.6 million m^3/year by DSI. In the implemented FREEWAT model, we estimated that water flows to Tuzla Lake was 1.82 million m^3/yr when there is groundwater pumping at a rate of 1.49 million m^3/yr and it was 3.12 million m^3 when there is no groundwater pumping. Overall, flows to Tuzla Lake estimated by the model and by DSI were in good agreement.

Finally, we compared the groundwater levels calculated with the model with measurement records from March 2016. As groundwater use does not start until May, we can assume that water levels in March represent the steady-state conditions. The comparison between observed and simulated water levels in March, shown in Fig. 7, show satisfactory agreement. Correlation coefficient calculated between observed and simulated heads was 0.58. In general, simulated heads are lower than observed heads, which might be related to specific conditions in the years 2015 and 2016. FREEWAT model was run with average conditions of the 1990-2015 period. 2015 was a year with higher than normal precipitation and groundwater recharge, which can explain the difference between simulated and observed heads for March 2016.

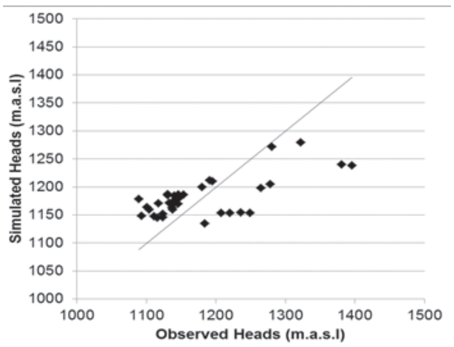

Fig. 7 - Observed and Simulated Heads. Observations are from March 2016.

Fig. 7 - Confronto dei valori osservati con quelli simulati. Le osservazioni sono riferite al Marzo 2016.

Model results

The model was run by activating net recharge (recharge-evapotranspiration) and groundwater abstraction. We also activated lake package for simulating Tuzla Lake and river package for simulating Değirmen River.

As can be seen in Fig. 8, the direction of groundwater flow from southeast to northwest is simulated. Groundwater discharges eventually to the Tuzla Lake and Değirmen River. Annual recharge to the groundwater system is about 5.27 million m^3 (Table 1). Almost all of this recharge is through infiltration of precipitation and a negligible amount of recharge is through infiltration from surface runoff. The water losses in the groundwater system in the Palas Basin during this simulation are due to leakage to rivers and lakes and groundwater pumping. River leakage is 2.25 million m^3/yr and discharge to Tuzla Lake is 1.53 million m^3/yr. Overall, groundwater pumping is 1.49 million m^3/yr (Table 1)

Examining the simulated water budget of the Tuzla Lake, we see that about 1.53 million m^3/yr of water is discharged to the lake by groundwater. Precipitation inflow is about 7.05 million m^3/yr and surface water inflow is about 12.61 million m^3/yr. Annual evaporation from Tuzla Lake is simulated as 21.19 million m^3/yr. Average water elevation at Tuzla Lake under reference condition is 1126.40 m.

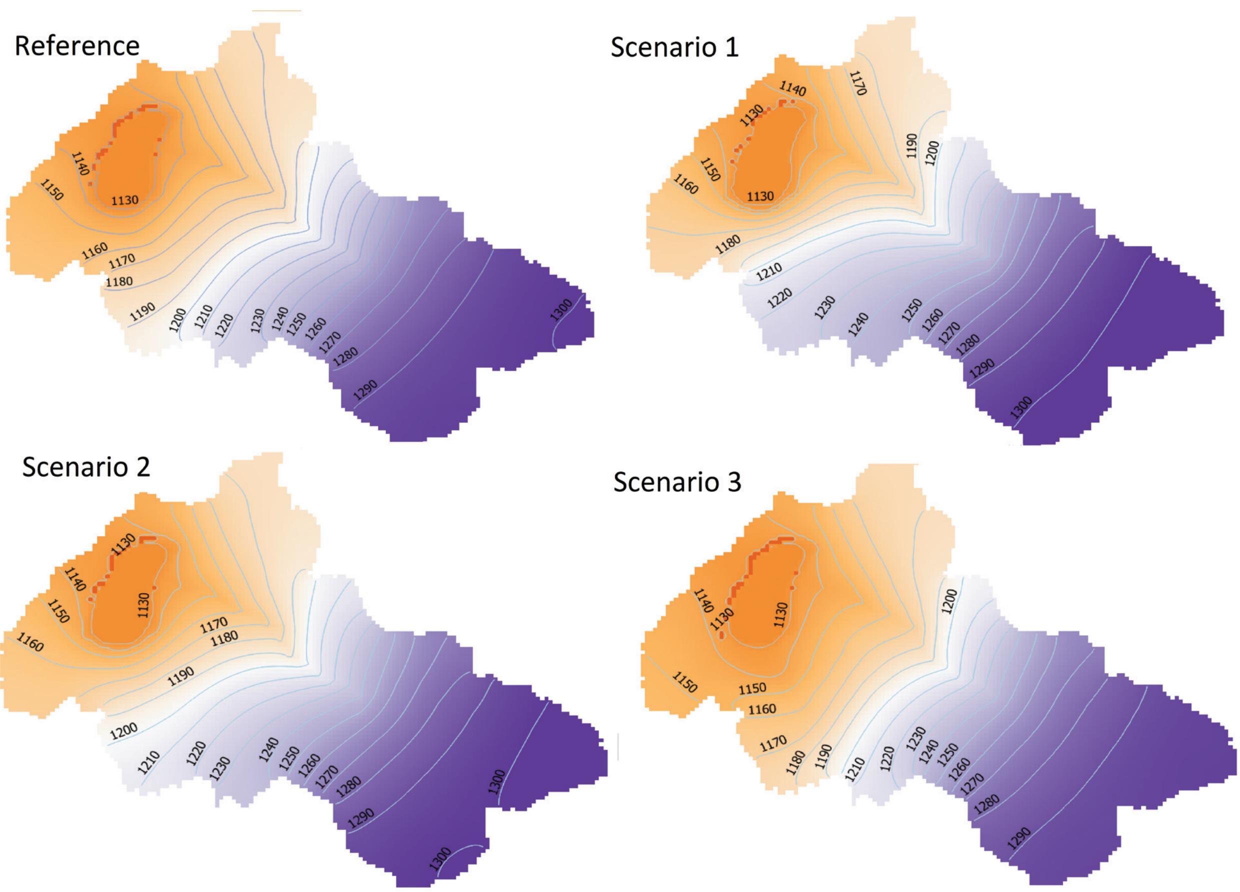

Fig. 8 -Groundwater levels under reference conditions and under Scenarios.

Fig. 8 - Livelli piezometrici relativi al modello di riferimento e agli Scenari Simulati.

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Tab. 1 - Groundwater budget under reference conditions and under Scenarios.

Tab. 1 - Bilancio idrico riferito al modello di riferimento e agli scenari simulati.

Condition	Reference	Scenario 1	Scenario 2	Scenario 3
INFLOWS (million m^3/year)				
River Leakage	0.18	0.16	0.16	0.18
Recharge	5.09	5.10	5.10	5.09
Total	5.27	5.26	5.26	5.27
OUTFLOWS (million m^3/year)				
River Leakage	2.25	3.12	2.68	1.82
Lake Seepage	1.53	2.14	1.84	1.22
Wells	1.49	0	0.74	2.23
Total	5.27	5.26	5.26	5.27

Water Management Scenarios

In the scenario analyses, we run simulations to evaluate the effects of groundwater abstraction rates. We compared the groundwater conditions under different abstraction scenarios with the condition with 1.49 million m^3/yr groundwater abstraction (reference condition).

The first water management scenario aimed at determining historical condition in the Palas Basin. The model was run by activating only groundwater recharge and no groundwater abstraction was added. Under the no abstraction scenario (Scenario 1), the analysis of the water budget shows that annual recharge to the groundwater systems is 5.26 million m^3 with some minor recharge from the river leakage. Groundwater discharge by river leakage is 3.12 million m^3/yr and seepage to Tuzla Lake is 2.14 million m^3/yr. If we compare the simulated results of Scenario 1 (no abstraction) with the simulation of the assumed abstraction condition (1.49 million m^3/yr) we note that, when groundwater pumping stops, river leakage increases by 0.87 million m^3/yr and discharge to Tuzla Lake increases by 0.61 million m^3/yr. Examining the estimated water budget of the Tuzla Lake under Scenario 1 (no abstraction), we see that about 2.14 million m^3/yr of water is discharged to the lake by groundwater. Precipitation inflows is 7.36 million m^3/yr and surface water inflows is about 12.61 million m^3/yr. Annual evaporation from Tuzla Lake is simulated as 22.11 million m^3/yr. Under Scenario 1, average lake stage is 1126.86 m. This elevation is 0.46 m higher than that of reference condition.

As the second water management scenario, we evaluated the effects of reduction in groundwater pumping. The groundwater abstraction was reduced by 50% to 0.75 million m^3/yr with respect to the reference condition (1.49 million m^3/yr). When groundwater pumping is simulated as 0.75 million m^3/yr, river leakage is 2.68 million m^3/yr and discharge to Tuzla Lake is 1.84 million m^3/yr. Groundwater abstractions are simulated as 0.74 million m^3/yr. If we compare the simulated results of Scenario 2 (0.75 million m^3/yr) with the simulation of the assumed abstraction condition (1.49 million m^3/yr) we note that river leakage increases by 0.43 million m^3/yr and discharge to Tuzla Lake increases by 0.31 million m^3/yr. Reducing groundwater pumping rates with respect to reference conditions, increases groundwater inflows to Tuzla Lake and river leakage. Examining the simulated water budget of the Tuzla Lake for 50% reduction in groundwater pumping rates with respect to reference conditions (Scenario 2), we can see that in that case 1.84 million m^3/yr of water is discharged to the lake by groundwater. Precipitation inflow is 7.20 million m^3/yr and surface water inflow is about 12.61 million m^3/yr. Annual evaporation from Tuzla Lake is simulated as 21.65 million m^3/yr. Under Scenario 2, average lake stage was calculated as 1126.67 m. This elevation is 0.27 m higher than that of reference condition.

As the third water management scenario, we evaluated the effects of increasing groundwater pumping. We increased the groundwater abstraction in the basin, with respect to the assumed average value of 1.49 million m^3/yr, by 50% to 2.25 million m^3/year. When groundwater pumping is simulated as 2.25 million m^3/yr, river leakage is 1.82 million m^3/yr and discharge to Tuzla Lake is to 1.22 million m^3/yr. Overall groundwater pumping is simulated as 2.23 million m^3. If we compare the simulated results of Scenario 3 (2.25 million m^3/yr) with the simulation of the assumed abstraction condition (1.49 million m^3/yr) we note that, when groundwater pumping is increased by 50%, river leakage decreases by 0.43 million m^3/yr and discharge to Tuzla Lake decreases by 0.31 million m^3/yr. Increasing groundwater pumping rates with respect to reference conditions, decreases groundwater inflows to Tuzla Lake and river leakage. When we examine the water budget of the Tuzla Lake, we see that about 2.3 million m^3 of water is discharged to the lake by groundwater. Precipitation inflows is about 7.5 million m^3 and surface water inflows is about 12 million m^3. Annual evaporation from Tuzla Lake was calculated as 22 million m^3. With groundwater pumping, average lake stage is calculated as 1126.14 m, which is 0.31 m lower than that of reference condition.

As a general result, the scenarios showed that the hydrology of Tuzla Lake is closely related to groundwater use in the Palas Basin. Increases in groundwater use cause decreases in groundwater flows to the lake and decreases water levels. As mentioned before, one of the major water problems in the Palas Basin is water level decreases in Tuzla Lake. Reversing this situation requires better control of groundwater pumping. However groundwater use in the basin is strongly linked with the socio-economic conditions in the basin.

Conclusions

This study aimed analyze surface water- groundwater interactions in the Palas Basin using groundwater modeling. Palas Basin is semi-arid, agricultural closed basin where problems appear due to competition between ecosystems and agriculture for scarce water resources. With this study, we simulated the groundwater component of the hydrologic system in the Palas Basin, represented the linkage between surface water and groundwater in the Palas Basin and understood the relationships between water management practices and water transport mechanisms. The effects of groundwater pumping on the on the Tuzla Lake were examined by running different scenarios.

The analysis showed that groundwater use in the Palas Basin directly affects surface and groundwater recharge in to Tuzla Lake. Water levels in the Tuzla Lake are already much lower than the conditions with no groundwater pumping. For hydrologic sustainability of the Tuzla Lake, there is an urgent need to consider agricultural water requirements together with water requirements of lakes and wetlands in the basin. However, this would require extensive analysis of socio-economic factors in the basin.

The Palas Basin model was developed with input data readily available from various institutions and previous projects or literature. Although the model provided satisfactory results, model performance could be improved by incorporating more field data and applying more rigorous model calibration. In the future, we plan to update the model when more field data become available.

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