Abstract  A numerical modeling case study of groundwater flow in a diffuse pollution prone area is presented. The study area is located within the metropolitan borders of the city of Izmir, Turkey. This groundwater flow model was unconventional in the application since the groundwater recharge parameter in the model was estimated using a lumped, transient water-budget based precipitation-runoff model that was executed independent of the groundwater flow model. The recharge rate obtained from the calibrated precipitation-runoff model was used as input to the groundwater flow model, which was eventually calibrated to measured water table elevations. Overall, the flow model results were consistent with field observations and model statistics were satisfactory. Water budget results of the model revealed that groundwater recharge comprised about 20% of the total water input for the entire study area. Recharge was the second largest component in the budget after leakage from streams into the subsurface. It was concluded that the modeling results can be further used as input for contaminant transport modeling studies in order to evaluate the vulnerability of water resources of the study area to diffuse pollution. **Keywords:** MODFLOW-2000; modeling; PEST; water budget model; recharge; Tahtali watershed-Turkey

INTRODUCTION

Groundwater recharge originating from precipitation or percolation of irrigation water are the dominant mechanisms that drive the transport of diffuse pollutants to the groundwater table. Therefore, estimation and quantification of groundwater recharge is an essential component of integrated watershed management practices. There are several methods to quantify groundwater recharge; Scanlon et al. (2002) provide a useful review on choosing the appropriate technique to determine recharge. The methods can be divided into physical, chemical (tracer) and numerical modeling approaches. One of the well-known physical methods is the water table fluctuation method (Healy and Cook, 2002), which is based on the premise that rises in groundwater levels in unconfined aquifers are due to recharge water percolating through the vadose zone. Groundwater dating (Blasch and Bryson, 2007) and the chloride mass balance methods (Wood and Warren, 1995) are examples for tracer methods to determine. On the other hand, numerical models are useful and robust tools to quantify recharge. Precipitation-runoff modeling or sometime referred to as watershed modeling is a surface-water focused approach, which generally yield groundwater recharge estimates as a residual term in the water budget equation (Wanke et al., 2008). These models are usually lumped and provide a single recharge estimate for the entire watershed. There are also groundwater-centered recharge estimate approaches; groundwater flow model calibration is
used to predict recharge rates from information of observed hydraulic heads, hydraulic conductivity and other parameters (Karadaş et al., 2007; Sanford, 2002).

The primary aim of this study was to develop and execute a numerical groundwater flow model for a semi-arid, environmentally stressed Tahtalı watershed in the metropolitan area of Izmir, the third largest city in Turkey. The recharge parameter of the model was determined by the model output of a lumped, transient precipitation-runoff model, which was independently executed. Among the purposes of the flow model was to use its results as input for a subsequent watershed nitrate transport study.

DESCRIPTION OF STUDY AREA

The Tahtalı dam reservoir (38°08’ N; 27°06’ E) is located 40 km south of Izmir and meets about 36% of the city’s total water demand. The catchment has an area of 550 km² and is surrounded by the Sandallı Mountain in the west and the Nif Mountain in the northeast (Figure 1). The study area extends further away from the watershed boundaries towards the Bay of Izmir and southeast towards the Torbalı plain. The climate of the region is typical Mediterranean and the long-term mean annual precipitation over the area is recorded as 690 mm. Most of the precipitation occurs in the period between October and May, whereas the rest of the year is dry. A total of 44 ephemeral creeks and their tributaries drain through the catchment area and feed the Tahtalı reservoir. The major inflows to the reservoir are from the north via Tahtalı and Şaşal streams. The Şaşal stream contributes 25% whereas the Tahtalı stream contributes 75% to the total inflow. The discharges of the other four inflowing streams are negligible (Çalışkan and Elçi, 2009). Quaternary aged alluvial deposits, Neogene age flysch, clayey limestone, allochthonous limestone, conglomerate and tuff formations comprise the geological structure of the study area (Figure 2).

According to the 2008 census data (TURKSTAT, 2008), 68000 inhabitants live within the boundaries of the Tahtalı catchment. The population density closer to the city center (north of the watershed) is much higher. The catchment area is under environmental stress, in particular with respect to groundwater. Some small communities in the catchment rely on groundwater from supply wells. On the other hand, there are many wells drilled in the surficial aquifer, which provide the much needed irrigation water for agriculture. The groundwater in the catchment is prone to contamination originating from domestic and industrial pollution sources located mostly in the medium- and long-distance buffer zones of the catchment. Furthermore, excessive withdrawal from the surficial aquifer due to increase in population and also periodic droughts that have become more pronounced and sustained due to climate change pose a serious threat to the quantity and quality of groundwater resources. The study area is also prone to diffused source pollution due to sewer leakages and cesspools in the urban part (north of the study area) and agricultural activities in the rural part (south of the study area) of the study area.
Figure 1. General location map of study area showing the model and the Tahtalı watershed boundaries
METHODS

Field Work and Data Collection

Any modeling study in particular groundwater flow modeling studies require extensive and accurate data to obtain reliable and useful results. Some data such as meteorological data (precipitation, evapotranspiration and temperature), flow rates for the Tahtalı stream and borehole logs to identify subsurface profiles were available. However, groundwater table elevations were not available and therefore field work was undertaken to measure the groundwater head in the surficial aquifer. Accessible wells mostly in the form of private irrigation wells were explored within the boundaries of the study area with the aim of obtaining a fairly homogeneous distribution of measurement points. The coordinates of 51 selected monitoring wells were recorded using a GPS device. The locations of the monitoring wells are shown in Figure 2. In order to have representative groundwater level data for the wet and dry period of the year, measurements were conducted twice in May and October 2007, respectively. All the measurements and other pertinent information was put in a GIS database for subsequent processing of modeling input data, and production of several maps for the visualization of study results.

The Groundwater Flow Model

The finite-difference saturated groundwater flow code MODFLOW-2000 (Harbaugh, 2000) was used to model the flow in the surficial aquifer of the Tahtalı watershed. The model was set up as a one-layer, regional steady-state model with a spatial resolution of 150 x 150m. The boundaries of the model were determined such that it encompasses the entire area of interest and coincides with hydrological boundaries, e.g. sea, lake, watershed boundaries. The boundaries of the model are shown in Figure 1. Three types of boundary conditions were used: constant-head (Dirichlet), no-flow (Neumann) and head-dependent (mixed-type Cauchy). Furthermore, more than 100 borehole logs were processed to determine the depth to the impermeable layers, which were subsequently interpolated to obtain the surface representing the bottom surface of the model layer. The top surface of the model was obtained directly from 90m resolution SRTM data.

Hydraulic conductivity and vertical groundwater recharge from precipitation were the key parameters of the model. In this study, recharge was considered as net recharge, i.e. the actual portion of water reaching the water table after being withdrawn by plants in the root zone, thereby eliminating the need for the evapotranspiration parameter. The model domain was split up into six hydraulic conductivity zones, each zone representing a different geological formation and thus expected to have different but uniform hydraulic conductivities (Figure 2). This parameter was handled as a calibration parameter, which was varied within a plausible range of values during the calibration process. The plausible range of hydraulic conductivities was known apriori based on the properties of the different formations published in the literature (Fetter, 2001; Spitz and Moreno, 1996). Similarly, the model domain was divided into recharge zones, in each of which recharge originating from the ground surface was assumed to be uniform (Figure 3). The recharge rate for each zone was unknown and thus was used as calibration parameters of the model, except for zone no.4, which represents the Tahtalı watershed. For this particular recharge zone, recharge was calculated with an independent, transient regional-scale precipitation-runoff model (Fistikoglou and Harmancioglu, 2001). The details of this model are explained in the next section. Other secondary model input parameters were the extraction rates of major agricultural, domestic and industrial water supply wells in the study area and the water surface elevations of streams.

The calibration of the groundwater flow model was performed automatically using the parameter estimation code PEST (Doherty, 2004). The model was calibrated to the wet season water table
depths measured in May 2007 at 51 wells, and subsequently the calibrated model was verified with an independent data set representing the dry season water table measured in October 2007 at the same wells. During the verification of the model, the boundary conditions and recharge rates were modified accordingly to match wet season conditions.

Figure 2. Geological map of the study area and locations of the groundwater level monitoring wells
Precipitation-Runoff Modeling to Estimate Groundwater Recharge

The recharge for the Tahtali watershed was determined using a water budget model that estimates the monthly surface water flow rates at the lowest pour point of the basin using monthly precipitation and evapotranspiration records. It also includes the calculation of the components actual evapotranspiration, interflow, baseflow, subsurface storage and percolation, the latter being used in this study as an input parameter of the groundwater flow model. All model parameters are considered to be averaged and representative of the entire watershed, in this case recharge zone 4,
as opposed to distributed models. The flow chart and equations used in the model are shown in Figure 4. The parameters and variables used are as follows:

\[ P_t: \text{total precipitation for month } t \text{ (mm/month)} \]
\[ ET_{\text{ref}}: \text{monthly total reference evapotranspiration (mm/month)} \]
\[ ET_{\text{pot}}: \text{monthly total potential evapotranspiration (mm/month)} \]
\[ \theta_i: \text{coefficient dependent on vegetation type} \]
\[ \alpha_i: \text{runoff coefficient dependent on land use and vegetation type} \]
\[ \beta: \text{interflow coefficient} \]
\[ \gamma: \text{baseflow coefficient} \]
\[ S_{\text{max}}: \text{Maximum storage capacity of the soil (mm)} \]
\[ SS: \text{vadose zone storage surplus (mm)} \]
\[ S_t: \text{vadose zone storage for month } t \text{ (mm)} \]
\[ G_t: \text{saturated zone storage for month } t \text{ (mm)} \]
\[ Q_{t1}, Q_{t2}, Q_{t3}: \text{surface runoff, interflow, baseflow} \]
\[ \Sigma Q_t: \text{total surface flow rate at the basin pour point for month } t \text{ (mm)} \]

\( P_t \) and \( ET_{\text{ref}} \) are the required input parameters that were obtained from meteorological monitoring stations. Using the relationships between the several compartments, \( \Sigma Q_t \) was successively calculated by the model for each month. The remaining coefficients were the model’s calibration parameters and were varied within defined ranges until a satisfying match between \( \Sigma Q_t \) and the observed surface flow rates of the Tahtalı stream was obtained. The model was run for the time period of October 1981 to May 2008. Observed flow rates were available for October 1981-October 1988, therefore the calibration period of the model was for this period. The regression and Nash-Sutcliffe coefficients were used as criteria to evaluate the performance of the model.

Recharge calculated by this model was averaged in time to yield appropriate input for the steady-state groundwater flow model. Calculated recharge values for the period November 2006-April 2007 was averaged and used as input for recharge zone 4 in the groundwater flow model. Similarly, the output for May 2007-October 2007 was representative of the dry period and hence was used as input for the verification of the calibrated model.
RESULTS AND CONCLUSIONS

The calibration of the precipitation-runoff model yielded regression and Nash-Sutcliffe coefficients of 0.85 and 0.83, respectively. The match between modeled and observed stream flow rates was satisfactory (Figure 5). Based on the precipitation-runoff model results, the percentage of precipitation that reached the water table in the form of recharge in the rainy winter months of the period 2003-2008 was determined to vary between 0 and 54.3%, depending on meteorological conditions of each year. The lower end of the range coincided with an extreme drought period in 2007, which was by chance also the period in which this study was conducted and the groundwater flow model was calibrated. Furthermore, the recharge ratio was calculated to be equal to zero for the unusually dry summer months that occurred in that same period (Figure 5). The recharge rate for the wet period of 2007 was 16 mm, which corresponded to an average recharge to precipitation ratio of 3.3%.

Figure 4. Components and flow chart of the water budget based precipitation-runoff model
The calibrated groundwater flow model yielded satisfactory calibration statistics; residuals were distributed randomly around zero and the residual mean, the absolute residual and the root mean squared residual (RMSD) were determined as 0.6, 11.0 and 16.4 m, respectively. The RMSD value was only 5% of the range of measured values. Overall, these values were acceptable within predefined model performance limits. It is evident in Figure 6 that the model yielded comparable water table elevations for most of the observation points; however, it was less successful for points located at higher elevations of the study site.

**Figure 5.** Results of the precipitation-runoff model; (top) hydrographs for the calibration period; (bottom) hydrographs for the predictive modeling period.
Calculated water table elevations and groundwater flow directions (Figure 7) were reasonable and consistent with field observations. Based on the modeling results a strong influx of groundwater toward the watershed is observed at the foothills of the Nif mountain, in the northeast of the study area. The flow directions around the reservoir significantly varied, influenced mainly by stream-aquifer interactions and local irrigation water withdrawals. Water budget results of the model revealed that groundwater recharge comprised about 20\% of the total water input for the entire study area. Recharge was the second largest component in the budget after leakage from streams into the subsurface. The modeling results also demonstrate that it is very likely that the reservoir water quality is influenced by activities in the rural part of the study area, e.g. the Cumavasi plain. However, to better evaluate the vulnerability of water resources in the area to diffuse pollution, a contaminant transport modeling study that is based on the presented flow model may be warranted.

It is demonstrated with this study that a robust modeling approach can be taken by combining results of a lumped precipitation-runoff model with a distributed groundwater flow model. Groundwater recharge in groundwater flow models is often one of the most uncertain model parameters since it is almost impossible to measure it directly in the field for large watersheds. Nevertheless, it is important to somehow quantify recharge, in particular for diffused pollution vulnerability studies.

![Graph of measured vs. calculated water table elevations](image)

**Figure 6.** Comparison of calculated water table elevations with measured value; straight line indicates perfect fit
Figure 7. Groundwater flow modeling results for the Tahtalı watershed
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