Simulation of Groundwater Flow in the Gediz River Basin

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Abstract: The objective of this paper is to present the approach and results of a groundwater flow modeling study that was conducted for the Gediz River Basin (GRB), located in western Turkey. The GRB is one of the most important, largest and stressed river basins in Turkey. This basin is agriculture-dominant; however significant competition for water exists among various stakeholders and sectors. The model is set up as a two-dimensional, finite-difference MODFLOW-2005 model that is solved for steady-state conditions, representing average annual groundwater flow in the basin. The main purpose of the groundwater flow model is to determine groundwater flow dynamics and water budget for the alluvial aquifers of the GRB. Pumping wells in the GRB predominantly withdraw water from these aquifers. A model-based estimate of the hydraulic conductivity distribution is also obtained. A two-stage modeling approach is taken to determine boundary conditions of the alluvial aquifer model domain. This approach results in two independently calibrated models that are referred as baseline and alluvial flow models. Modeled groundwater heads of both models provide an acceptable fit to observed data. The range of hydraulic conductivity (K) values is from 0.01 to 4451 m/d indicating a very heterogeneous aquifer. The median K value is 34.92 m/d and the standard deviation is 366.45 m/d. According to the baseline flow model budget, it can be concluded that the most significant groundwater input for the entire GRB is leakage from surface water such as dam reservoirs and the Gediz riverbed. In the alluvial aquifer, surface water still plays an important role in the water balance, however lateral flows across aquifer boundaries are the most important component. Also, groundwater extraction is larger than groundwater recharge by precipitation.

Keywords: watershed, groundwater model, MODFLOW, Turkey

1. INTRODUCTION

Numerical groundwater flow models are widely used in hydrogeological studies at the river basin scale. They can serve different purposes that depend on the objectives of the hydrogeological study. Most groundwater flow models are supporting tools that aid river basin authorities in making decisions on groundwater management issues. Often the question posed is, “how much water is available for sustainable withdrawal?” In some cases it is also valuable to know how deep to drill to withdraw groundwater that is safe and sustainable or what the dominant direction and magnitude of groundwater flow is, in particular for cases of contaminated aquifers. Groundwater modeling results provide also concrete numbers in terms of water budgets that can guide decisions related to water allocations among water stakeholders.

The objective of this paper is to present the approach and results of a groundwater flow modeling study that was conducted for the Gediz River Basin (GRB), located in western Turkey. This study is part of a comprehensive 2-year long hydrogeological study (DSI, 2014) of the GRB that was supervised by the State Hydraulic Works (DSI) of Turkey. The model is set up as a two-dimensional, steady-state finite-difference MODFLOW-2005 flow model (Harbaugh, 2005) that is solved for average annual groundwater flow condition. The main purpose of the groundwater flow model is to determine groundwater flow dynamics and water budget for the alluvial aquifers of the GRB. Pumping wells in the GRB predominantly withdraw water from these aquifers. A model-based estimate of the spatial hydraulic conductivity distribution is also obtained.

2. DESCRIPTION OF STUDY AREA

The GRB is one of the most important, largest and stressed river basins in Turkey. It is located in the Aegean region between 26° 42′ - 29° 45′ eastern longitudes and 38° 04′ - 39° 13′ northern latitudes. GRB has a drainage area of 17146 km^2 and it covers about 2.2% of Turkey’s total area. This basin is agriculture-dominant; however significant competition for water exists among various stakeholders and sectors. A topographical map of the GRB is shown in Fig.1.

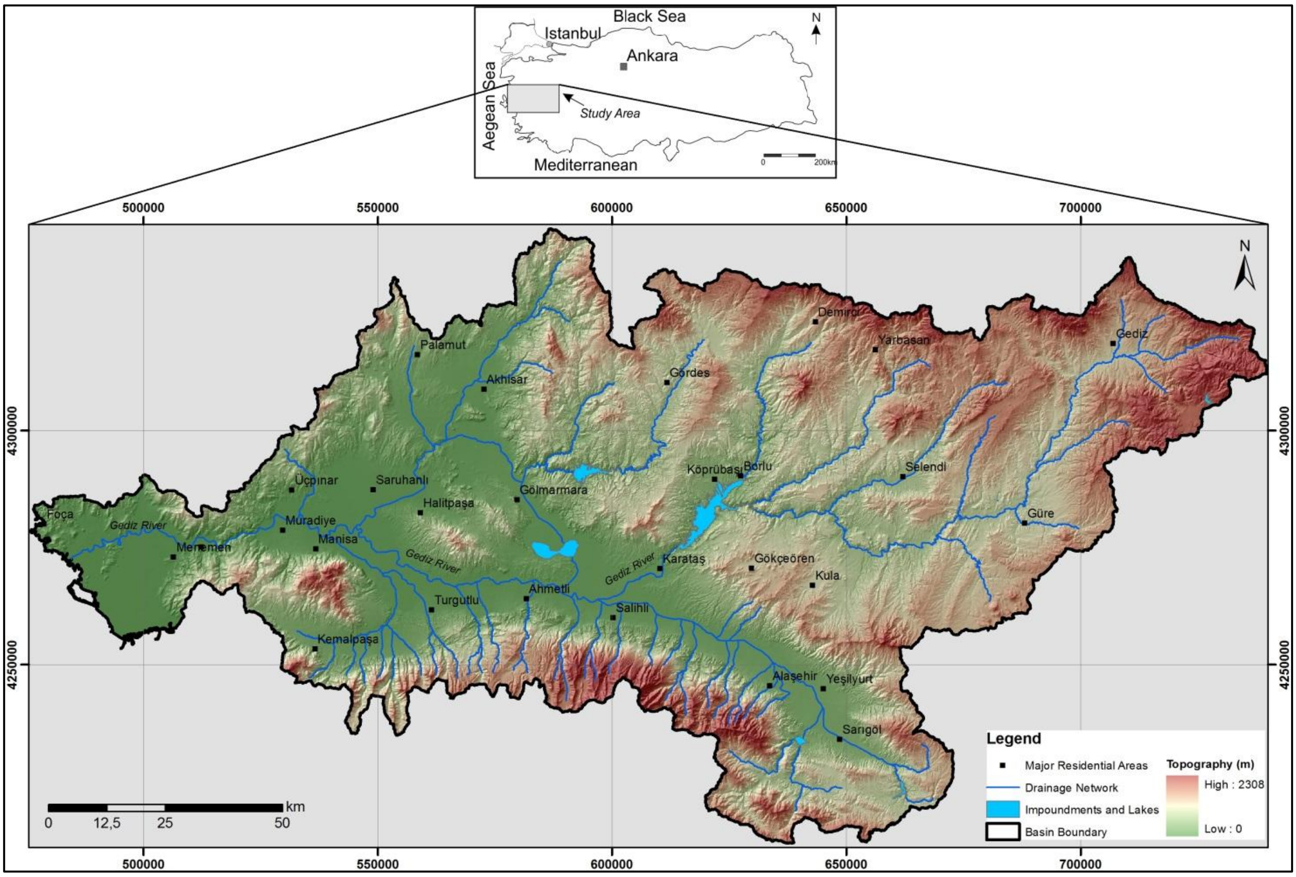

Figure 1. Map of Gediz River Basin

The basin exhibits typical Mediterranean climate with hot, dry summers and cool, rainy winters. Long-term mean annual temperature and precipitation are 15.2 °C and 617 mm (DSI, 2014), respectively. As of 2012, about 1.733 million people live within the boundaries of GRB. Main socio-economical activities are agriculture, animal husbandry, food industry, textile industry and mining. The agriculture sector is the most important water consumer in the GRB. Based on DSI (2014), an area of approximately 351,000 hectares is irrigated and is subject to extensive agricultural practices. The main crops cultivated are cotton, grapes, maize and olives.

3. MODELING APPROACH

3.1 Model Domain, Boundary Conditions and Discretization

Groundwater bodies of the GRB are grouped into three major hydrogeological classes; (1) sedimentary units with extensive groundwater, (2) consolidated units with local groundwater and (3) consolidated units with limited groundwater. Sedimentary units with extensive and abundant groundwater are mainly formed by alluvial deposits. These units are referred to as alluvial aquifer of the GRB which is developed mostly in the E-W directional Gediz graben area. The GRB alluvial aquifer comprises an important fraction of the total groundwater potential in the basin. Therefore the main objective is to simulate groundwater flows and calculate water budgets for this aquifer.

From a modeling point of view, the boundaries of the alluvial aquifer are ambiguous. Therefore a two-stage modeling approach is taken to determine boundary conditions of the alluvial aquifer model domain. In the first stage, a general regional-scaled model is set up for the entire basin (baseline flow model). In this case, the model domain boundaries are coincident with GRB boundaries. These are assigned as no-flow boundary condition, except for the Aegean Sea coastline, which is assigned as specified-head boundary condition representing the mean sea level of 0 m. The baseline flow model has a spatial resolution of 500 × 500 m, featuring a model grid with 68,761 active nodes. In the second stage, an alluvial aquifer groundwater flow model (alluvial flow model) is set up that has boundaries coincident with hydrogeological boundaries of the alluvial layer. The groundwater head values computed from the baseline flow model are assigned as specified-head boundary conditions to the alluvial flow model. Model data, including layer elevations and hydraulic conductivity are interpolated from the baseline flow model. Other data such as pumping wells, rivers and streams, lakes and springs are represented with the same data as in the baseline flow model. The alluvial flow model has a finer resolution (250 × 250 m) with a total of 61,437 active nodes in the model grid. The total area of the alluvial flow model is 3839.8 km^2. The extent and boundaries of model domains is presented in Fig. 2.

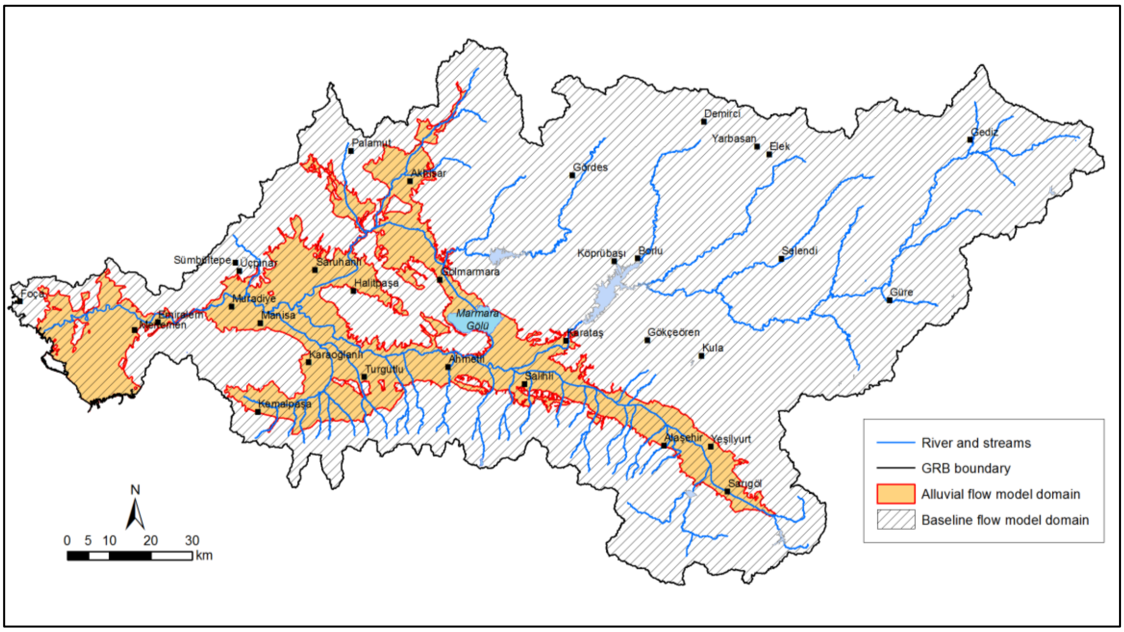

Figure 2. Model domains used in the two-stage modeling approach

Due to data limitations, both models are steady-state and two-dimensional, comprising of a single layer that represents the main hydrogeological unit. Top elevations of the model layer are determined using digital elevation model data of the area. Layer bottom elevations are calculated using lithology data from well logs. Well logs are examined for the depth of the base rock, which is conceptualized as a no-flow boundary in the flow model. Fig. 3 shows an isopach map of the alluvial flow model domain.

3.2 Hydraulic Conductivity and Groundwater Recharge

Hydraulic conductivity (*K*) and groundwater recharge are critical parameters in groundwater flow modeling studies. Basically a significant part of the information obtained from analysis of geology, meteorology and hydrogeology data is in some way incorporated in the determination of these parameters. In this study, the spatial distribution of K is obtained by interpolating K values that are available for 340 wells within the GRB. The range of measured K data is 2.1×10^{-3} – 7958 m/d with a median of 1.88 m/d. Because of the uncertainty associated with the K data, this parameter is adjusted during the calibration of the model.

Groundwater recharge can be handled in different ways. In some studies, recharge and evapotranspiration are considered as two separate parameters, whereas in others it is considered as net recharge. In this study the latter approach is taken. Net recharge is defined as the fraction of infiltrating precipitation water that reaches the water table after evapotranspiration. Recharge is defined in both flow models as a distributed parameter calculated using areal distributions of precipitation and evapotranspiration. Annual average values are used in the determination of recharge thereby yielding the annual average groundwater recharge rate for the GRB.

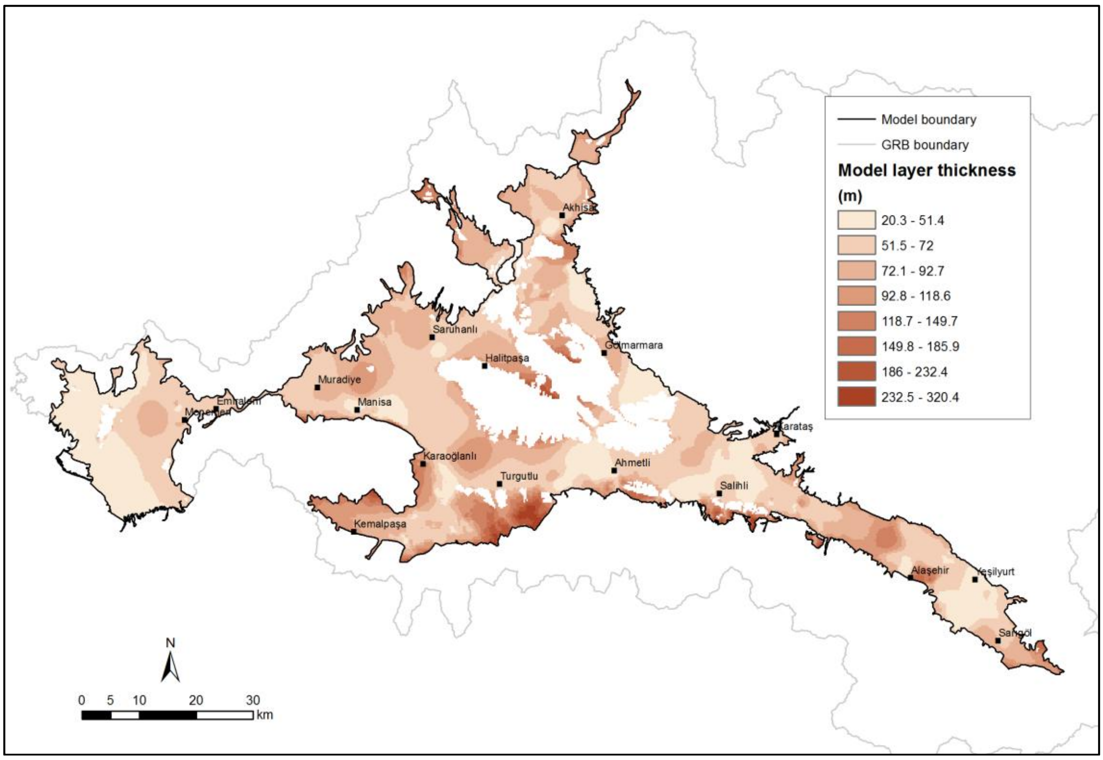

Figure 3. Isopach map of alluvial flow model domain

3.3 Sources and Sinks

The Gediz River and its tributaries are simulated in the baseline and alluvial flow models using MODFLOW’s RIV package. A total of 4382 and 3543 grid cells are assigned as river sources/sinks for the baseline and alluvial flow models, respectively. Conductance, river stage elevation and river bottom elevation are the input parameters for these cells. The conductance parameter itself is a lumped parameter that combines river width, riverbed thickness and hydraulic conductivity of the riverbed. The latter two variables are assumed as constants for the entire model domains, however depending on the approximated width of the river, conductance values per meter length of river range from 10 to 50 m^2/d. Annual average river stage elevations are assigned directly from stream gage measurements. RIV cells are head-dependent, therefore depending on the calculated groundwater head within a RIV cell, rivers assigned in the model act as a water source or sink.

There are 14 lakes in the GRB, eleven of them being dam reservoirs or irrigation impoundments. These are approximated in the flow models as general head boundaries. A total of 793 and 1037 general-head boundary grid cells are assigned in the baseline and alluvial flow models, respectively. Similar to the approximation for rivers, general-head boundary cells are also head-dependent.

Therefore, lakes can act as sources or sinks, depending on the relation between calculated groundwater head and assigned lake water level. Water level records of September 2013 and April 2014 are used to determine representative annual lake water levels. Conductance parameter values for lake general-head boundary cells are estimated using a constant lake sediment thickness of 3 m and sediment hydraulic conductivity of 10 m/d.

Groundwater extraction wells constitute the most important artificial groundwater sink in the GRB. These wells mainly extract groundwater for drinking water, irrigation and industrial process water. MODFLOW's WEL package is used to simulate groundwater extraction. Based on the hydrogeological study report by DSI (2014), it is estimated that more than 10,000 active wells operate within the GRB boundaries. However, data pertinent to location and pumping rates do not exist for a significant portion of these wells. Conclusively, only extraction wells that have coordinates and average pumping rates are used in this modeling study. Furthermore, wells with relatively low pumping rates, i.e. less than 100 m^3/d are excluded from the model database. This database contains a total of 2200 wells, from which 1211 and 706 are considered in the baseline and alluvial flow models, respectively. The pumping rates in the baseline flow model are in the range of 100.32 – 116,601.60 m^3/d and the average rate is 1877.37 m^3/d. Wells in the alluvial flow model have a pumping rate range of 103.68 - 116,601.60 m^3/d and an average of 2801.63 m^3/d. If more than one well coincide within a single grid cell, pumping rates of the wells are summed and simulated as a single well.

Finally, springs are also included in the groundwater flow model. Only springs with a discharge rate higher than 100 m^3/d are defined in the model domain. These were conceptualized in MODFLOW using the drain package (DRN). Drain nodes defined in the groundwater flow are head-dependent as river (RIV) and general-head-boundary grid cells, however they can only act as groundwater sinks. The drain flow rate, i.e. the spring discharge rate, is a function of the spring conductance value, spring elevation and the calculated groundwater head value of the DRN grid cell. A spring conductance value of 20,000 m^2/d is initially assumed as constant for all springs. This parameter is altered later in the calibration process to match the simulated discharge rate to the field measured rate. The ground elevation at the spring location is assigned as the spring elevation parameter in the model.

3.4 Model Calibration

The objective of calibration is to alter model parameters within defined ranges in order to minimize the overall error between calculated and measured groundwater levels. Thereby, a globally optimum solution of the groundwater flow model is achieved with an optimum spatial distribution of model parameters. During the model calibration in this study, hydraulic conductivity (*K*) is adjusted to obtain an acceptable correlation between measured and simulated groundwater head values. The spatial distribution of *K* is determined by the pilot point method. Pilot points are basically locations in the modeling domain, where estimations of *K* are known. These estimations are assigned as initial parameter values and are interpolated over the model domain to obtain the parameter distribution. Pilot point values are systematically altered, and parameter distributions updated in the calibration process until an optimum solution is reached. To facilitate model calibration, the parameter estimation code PEST (Doherty, 2004) is implemented in this study.

Several statistical criteria are tracked during the calibration. These are mean error (ME) (Eq.1), mean absolute error, sum of squared errors and the root mean squared error (RMSE) (Eq.2).

$$ME = \frac{1}{n}\sum_{i=1}^{n}\left(h_o - h_m\right)_i \tag{1}$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(h_o - h_m\right)_i^2} \tag{2}$$

h_o and h_m in Equations 1 and 2 are observed and calculated groundwater head values, respectively; n is the number of head observations. Both models are calibrated independently, however using the same head measurement data as the calibration targets. As previously mentioned, the calibrated output of the baseline flow model is used to determine boundary conditions of the alluvial flow model. The groundwater flow models are developed to estimate annual average flow conditions in the alluvial aquifer of the GRB. Therefore, head measurement data from September 2013 and April 2014 is averaged and assumed as annual mean groundwater level. Groundwater head data from 529 observation wells are used to calibrate the baseline flow model, whereas 246 observations for the alluvial flow model. The calibration range for K is set to 0.01 – 4500 m/d, which is based on identified geological zones in the GRB.

4. RESULTS

4.1 Baseline Flow Model

The baseline flow model is executed after final calibration to obtain the steady-state solution for groundwater flow in the GRB. A reasonable correlation between simulated and observed groundwater heads is obtained as shown in Fig. 4. As an indicator for the goodness of match between observed and calculated head values the Pearson correlation coefficient is determined as 0.934 with the assumption that head values fit normal distribution. Based on calibration results, the mean error (ME) is 15.74 m and the root mean squared error (RMSE) equals 110.79 m. The RMSE is about 14.3% of the observed data range, which is acceptable considering the size and complexity of the watershed.

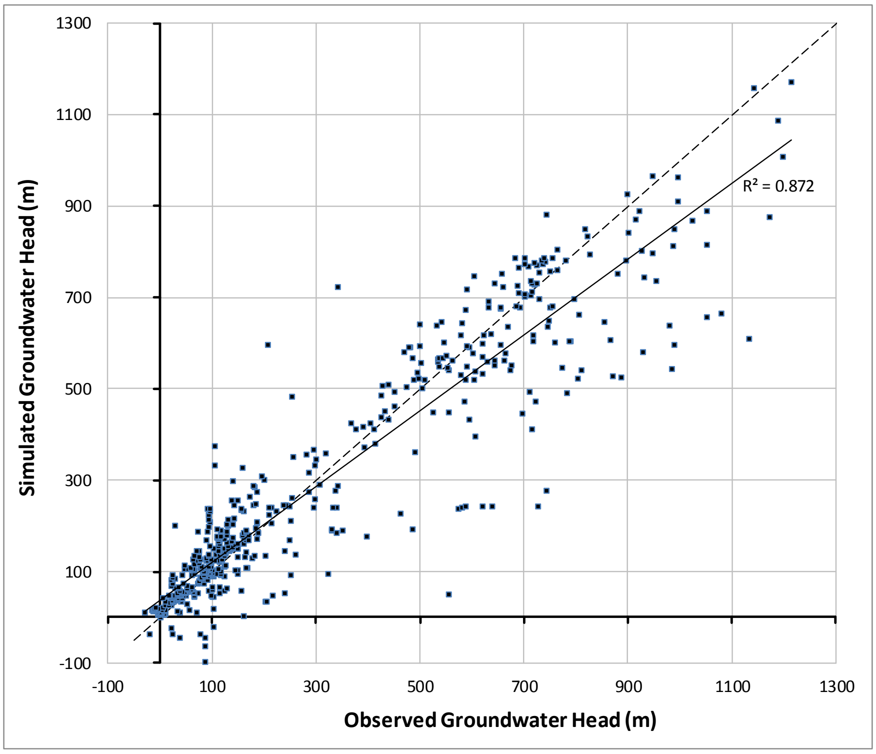

Figure 4. Comparison of observed and simulated groundwater heads for the baseline flow model

The distribution of calculated head values is shown as a contour map in Fig. 5. The range of groundwater head is large, values ranging from -50.6 m near the Aegean coastline to 1051 m at the highlands of the GRB. Results of the baseline flow model are further evaluated in terms of the groundwater budget. Other interpretations with respect to groundwater flow direction, surface water interactions etc. are not provided in the scope of this paper since the emphasis is placed on the outcome of the alluvial aquifer flow model.

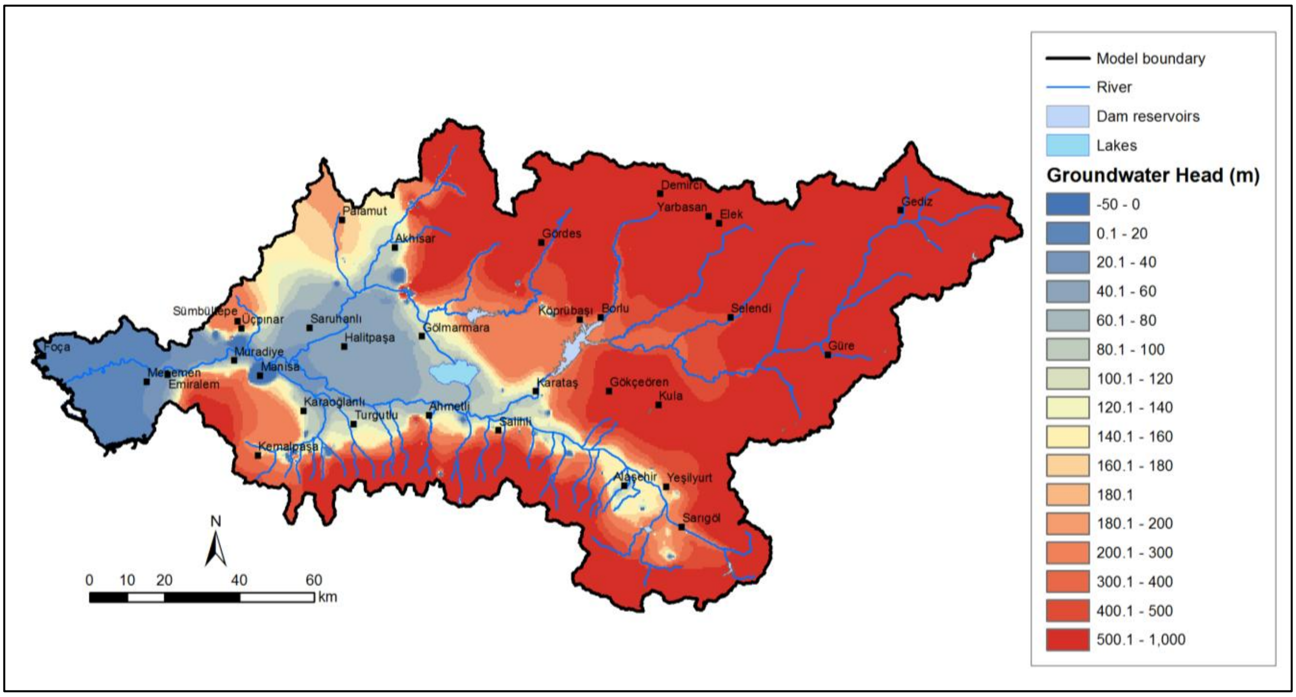

Figure 5. Groundwater head contour map for baseline flow model

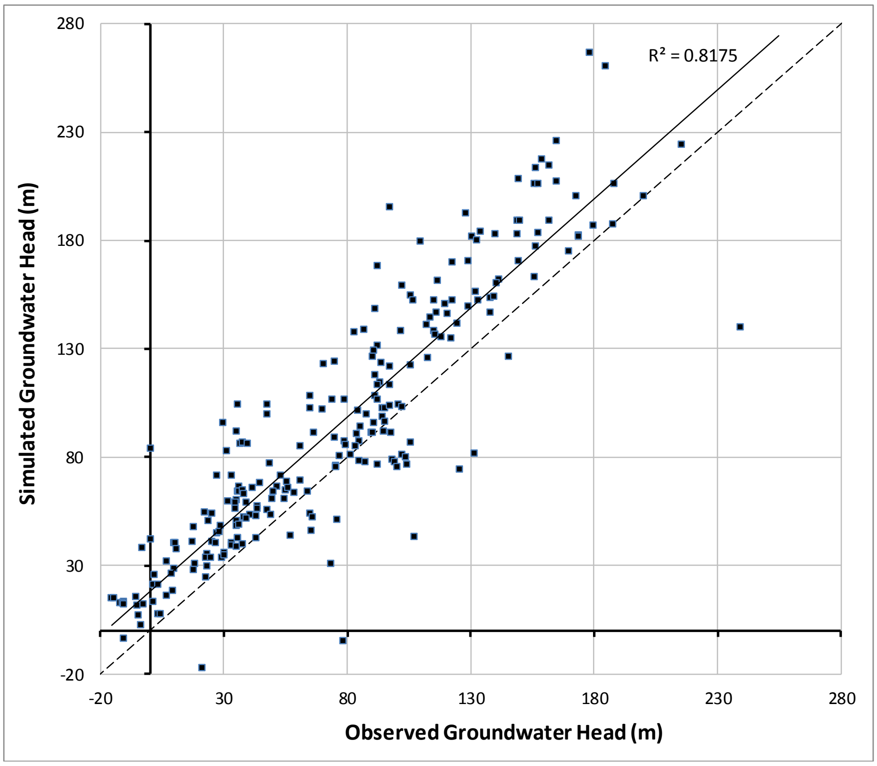

Figure 6. Comparison of observed and simulated groundwater heads for the alluvial flow model

4.2 Alluvial Flow Model

In the second stage of this modeling study, the alluvial flow model is run and calibrated. Correlation between post-calibration and observed head values is acceptable with regression and

Pearson correlation coefficients of 0.8175 and 0.904, respectively. Comparison of calculated and observed heads is given in Fig. 6, which implies good correlation. However, it appears that the model slightly overestimates groundwater levels in the alluvial aquifer. This is also apparent in the calibration statistics where ME = -18.40 m and the RMSE = 38.99 m. The RMSE to observation range ratio is 14.4 %.

The range of calculated groundwater head values in the alluvial aquifer is -50 m – 568 m. The distribution of heads for the alluvial aquifer is shown in Fig. 7 as line contour map. Here it is evident that head gradients are very steep resulting in large groundwater fluxes toward the alluvial plains in the GRB. The dominant groundwater flow direction is roughly from east to west. Furthermore, lateral recharge from mountain foothills appears to have a significant role in the groundwater dynamics of the basin. Lake Marmara has no obvious effects on the groundwater flow regime, however the main reach of the Gediz River diverts groundwater flow, thereby indicating a strong influence of surface water – groundwater interaction. Fig. 8 illustrates gaining and losing portions of the Gediz River and its tributaries as determined by the alluvial flow model. It can be concluded that water is lost to the alluvial aquifer along most parts of the main reach of the Gediz River. Another feature that can be distinguished is the depression cone around in the Manisa region, where large volumes of groundwater is extracted by the Göksu wellfield. These wells supply water to the city of Izmir, meeting about 30% of the total water demand.

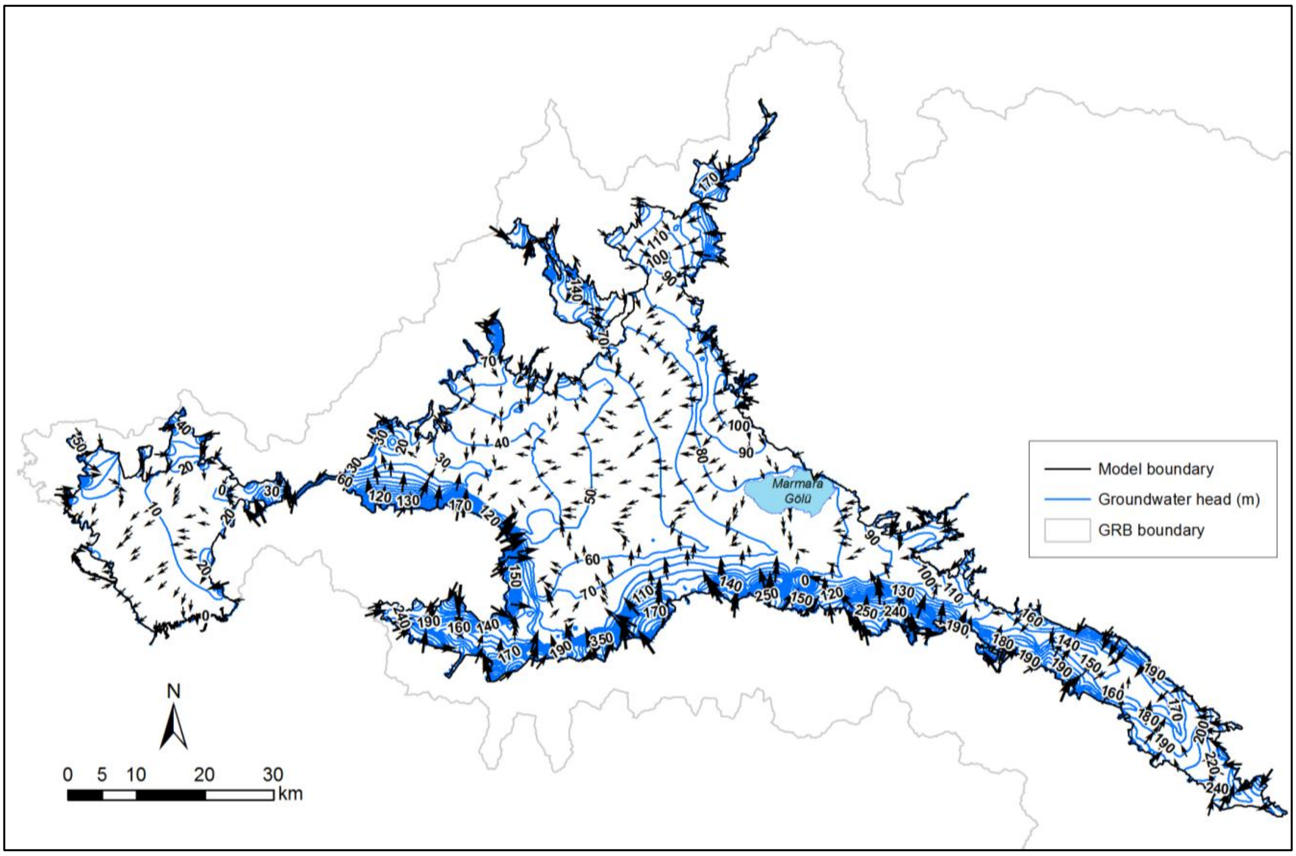

Figure 7. Groundwater heads and flow directions calculated with the alluvial flow model (arrow sizes are proportional to flow velocities)

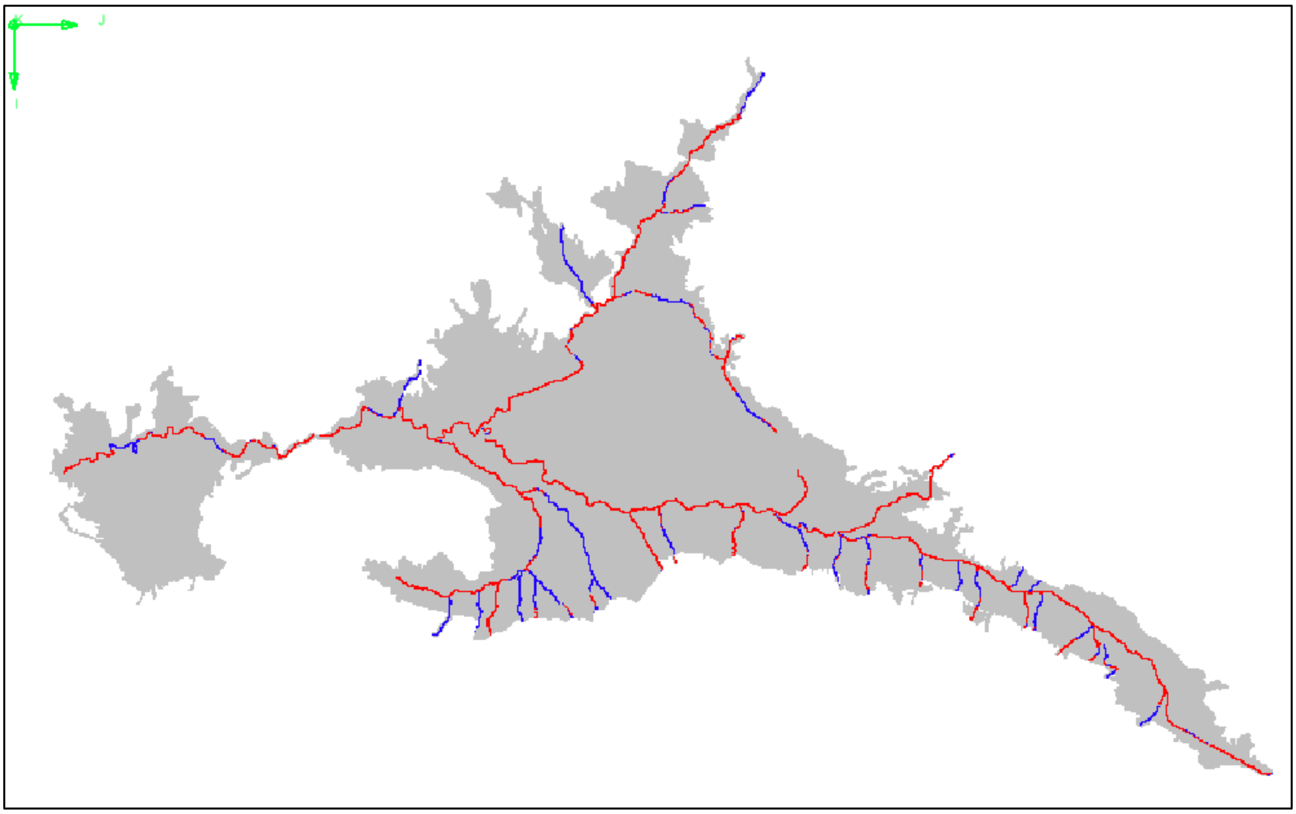

Figure 8. Aquifer-Stream interactions determined by alluvial flow model (losing and gaining streams are marked red and blue, respectively)

An important output of this modeling study is the final distribution of hydraulic conductivity (K) after calibration of the alluvial flow model (Fig. 9). The range of K values is from 0.01 to 4451 m/d indicating a very heterogeneous aquifer. The median K value is 34.92 m/d and the standard deviation is 366.45 m/d. It is evident that K values exceed 1000 m/d in the Menemen plain, located at the westernmost edge of the GRB. This plain is known for intense agricultural activities and seawater intrusion impacts on groundwater quality. Areas that exhibit K less than 1 m/d are limited in extent.

4.3 Simulated Annual Groundwater Budget

Components of the groundwater budget that represent annual flowrates of groundwater recharge and discharge under steady-state conditions are determined based on the model results. The groundwater budget for both models is shown in Fig.10. According to the baseline flow model budget, it can be concluded that the most significant groundwater input for the entire GRB is leakage from surface water such as dam reservoirs and the Gediz River. In the alluvial aquifer, surface water still plays an important role in the water balance, however lateral flows across aquifer boundaries are the most important component. Also, groundwater extraction is larger than groundwater recharge by precipitation.

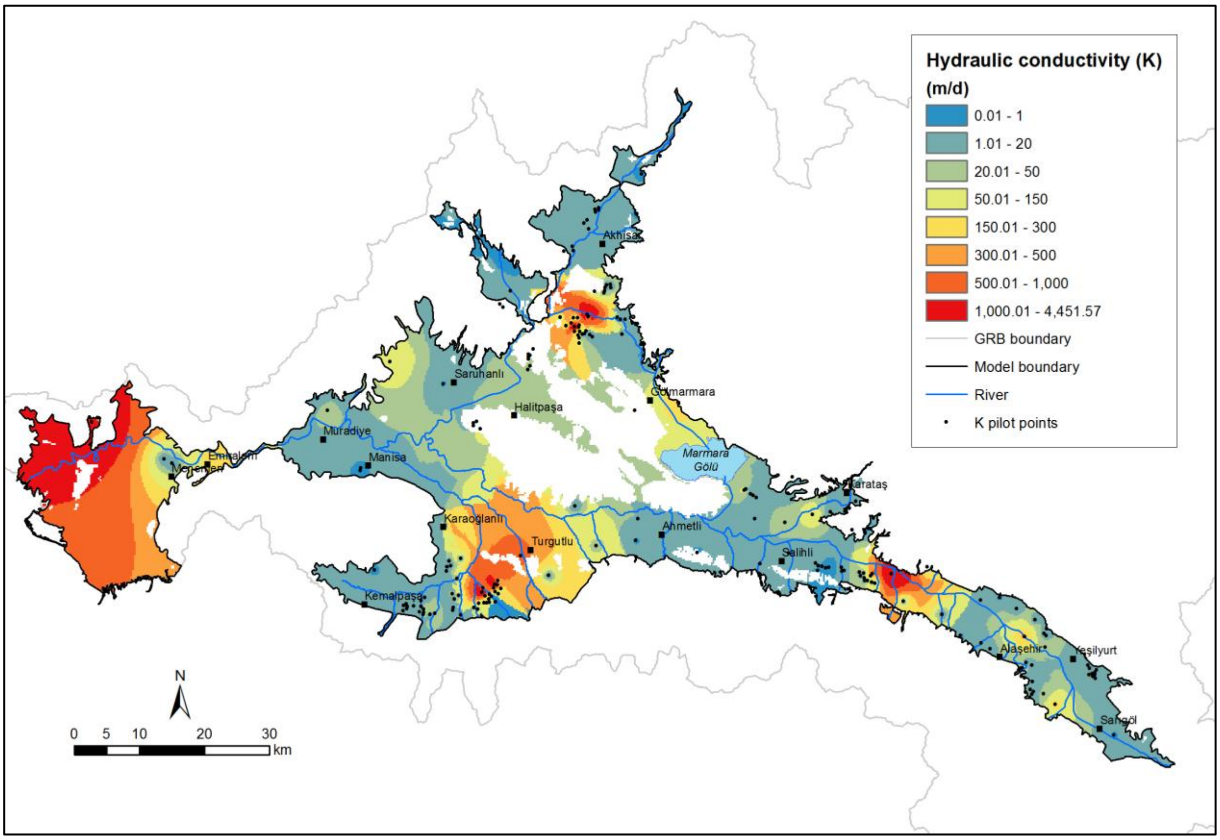

Figure 9. Hydraulic conductivity distribution after calibration of the alluvial aquifer flow model

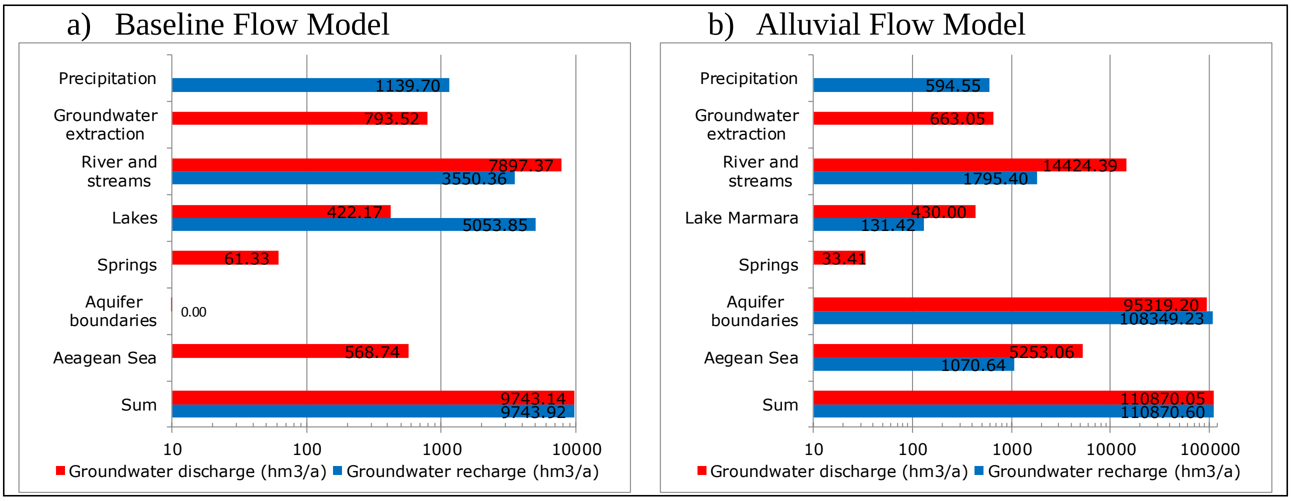

Figure 10. Calculated groundwater budget for a) baseline and b) alluvial flow models

According to model results, the total groundwater discharge rate from springs within the alluvial zone is 33.41 hm^3/a. Calibrated spring conductance values, simulated and observed discharge rates are given in Tab. 1. Calibration targets for spring discharges are determined based on standard deviations of observations and assuming a 95% statistical confidence level. It can be concluded that the model provides a good match between observed and calculated discharge rates, given that the spring discharges can fluctuate significantly during a year.

Table 1. Modeling results for major springs in the GRB

Spring name	**Observed mean annual discharge rate (hm^3/a)**	**Standard deviation of observations (hm^3/a)**	**Calibrated spring conductance (m^2/d)**	**Calculated steady-state discharge rate (hm^3/a)**
Akpınar (Gölmarmara)	17,906	16,647	5500	17,811
Beşgöze (Akhisar)	2,171	2,742	80000	0,237
Nazarköy (Kemalpaşa)	0,753	0,372	50	0,946
Soğukpınar (Kemalpaşa)	0,699	0,186	50	1,241
Çapaçarık (Manisa)	0,378	0,375	50	1,200
Gökbel (Akhisar)	*n/a*	n/a	20000	11,974
				Total = 33,408

5. CONCLUSIONS

The GRB is considered to be important and many studies and projects focused on this area in the recent past. It is significant in terms of its size, hydrogeological complexity, intense agricultural activity and pronounced groundwater use. The groundwater flow model presented in this paper is the first ever developed for this basin. Therefore, it is subject to further improvement and refinement. It provides valuable estimates for the water management authorities. As with all groundwater flow models, there are some limitations with the utilization of the model and issues that affect the reliability of model results. The model is run as steady-state since a sufficient number of temporal head observations did not exist. Furthermore, it is set up as a single layer model which prevents the resolution of vertical flow components. However, the ratio of the thickness of the aquifers to the lateral dimension of the basin warrants the use of such a two-dimensional model. The reliability of the alluvial flow model is higher than of the baseline flow model due to a more realistic definition of boundary conditions. Since unregistered groundwater pumping wells cannot be defined with respect to locations and pumping rates, the model is likely to underestimate the total withdrawal rate of groundwater, which can limit the reliability of model results to a certain extent.

As a conclusion of this study combined with the outcomes of the hydrogeological study of the GRB (DSI, 2014), groundwater levels have been declining for the past 20 years under the influence of intensive agricultural activities and increasing water demand due to increasing population. The decline in groundwater levels particularly caused salinization of the coastal aquifer in the Menemen plain, located in the west of GRB. This fact is also revealed partly in the groundwater flow model results. Furthermore, several large springs in the GRB have dried in the past, thereby decreasing baseflow and surface water flow rates. In conclusion, for the sustainable use of water in the GRB, basin management plans must be urgently implemented, a holistic perspective and practice of groundwater and surface water planning must be provided and groundwater withdrawal must be monitored.

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