Groundwater balance estimation and sustainability in the Sandıklı Basin (Afyonkarahisar/Turkey)

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The Sandıklı (Afyonkarahisar) Basin is located in the southwest of Turkey and is a semi-closed basin. Groundwater is widely used for drinking, domestic and irrigation purposes in the basin. The mismanagement of groundwater resources in the basin causes negative effects including depletion of the aquifer storage and groundwater level decline. To assure sustainability of the basin, determination of groundwater budget is necessary. In this study, the water-table fluctuation (WTF) and the meteorological water budget (MWB) methods were used to estimate groundwater budget in the Sandıklı basin (Turkey). Conceptual hydrogeological model of the basin was used for understanding the relation between budget parameters. The groundwater potential of the basin calculated with MWB method as 42.10×10^6 m³/year. In addition, it is also calculated with simplified WTF method as 38.48×10^6 m³/year.

1. Introduction

The Sandıklı Basin is located in the Afyonkarahisar within western Anatolia (figure 1) and covers an area of about 1556 km². It is one of the largest agricultural areas in the inner Aegean region of Turkey. The basin is a semi-closed basin due to discharge of surface water to the Büyük Menderes River via Kestel creek. Groundwater is widely used for drinking, domestic and irrigation purposes in the basin. There are 1150 drilling wells (shallow and deep) within the porous aquifer in the basin. Excessive groundwater withdrawals for irrigation have caused rapid declines in groundwater levels during the past two decades in the basin. Nowadays, although drilling of new wells has been limited by administrators, the problem of the local community due to increase in the irrigation water demand remains unresolved. Therefore, the determination of groundwater potential is of great importance for sustainable water management in the basin.

Groundwater reservoirs are also an important water resource both for the maintenance of the

natural environment and for human needs. Groundwater can be regarded as a renewable natural resource if there is a balance between recharge and abstractions of the aquifer (Voudouris 2006). Groundwater recharge and discharge are critical to understand the hydrologic cycle and to manage water resources. Good groundwater resources management practices require developing a water budget approach on a regional or large scale for an entire aquifer or geographic region (Cherkauer 2004). The sustainable management of the groundwater resources especially in basins depends on a detailed understanding of the regional hydrology and hydrogeological processes. In other words, understanding the groundwater reserve (potential and/or budget) is an essential pre-requisite for managing the groundwater system sustainably. Therefore, a well-known conceptual hydrogeological model of the basin is of great importance. The model plays a very useful role in the recharge estimation process (Scanlon *et al.* 2002). This model is used in the groundwater resources management plan.

Keywords. Groundwater basin; sustainable usage; water budget; Turkey.

In addition, the correct determination of the groundwater budget in a basin is also associated with selection of suitable budget calculation method. Different techniques are used to calculate the groundwater recharge and discharge amount; however, choosing appropriate techniques are often difficult. Various factors need to be considered when choosing a method to quantify recharge. A thorough understanding of the attributes of the different techniques is critical (Scanlon *et al.* 2002). The detailed studies of groundwater budget assessment in different basins were made by many researchers (Alamin 1979; Kim *et al.* 2001; Bredehoeft 2002; Scanlon *et al.* 2002; Welsh 2002; Devlin and Sophocleous 2004; Dünkloh 2005; Al Obied 2007; Nilsson *et al.* 2009; Elsheikh *et al.* 2011). Lee *et al.* (1999) and Chen *et al.* (1999) estimated groundwater recharge by adopting the water-budget model, combining the rainfall data and soil parameters with the infiltration model. Finch (1998) used a simple water-balance model to study effects of land surface parameters on groundwater recharge. Lee *et al.* (2000) also applied the water-balance method in conjunction with an independent estimation of recharge from a finite-difference simulation of groundwater levels. Simmons and Meyer (2000) provided a simplified model for the transient water budget of a shallow unsaturated zone to estimate groundwater recharge. Dünkloh (2005) applied the physical water balance model (MODBIL) for the determination of the water budget. The main water balance components such as precipitation, actual evapotranspiration, run-off and groundwater recharge are given out in this method. The model results provide an insight into the physical system, e.g., interactions of the regional, meteorological, hydrological, and hydrogeological processes, the intra- and inter-annual variability, and the impacts on the regional water resources. According to Yin *et al.* (2011), groundwater recharge is a key factor in water balance studies, especially in (semi-)arid areas. For the estimation of groundwater recharge, they used multiple methods such as water-table fluctuation, Darcy's law and the water budget. Elsheikh *et al.* (2011) investigated the groundwater budget for the alluvial aquifer in Sudan. In this study, the input to the groundwater is mainly represented by the infiltration from surface water, direct infiltration and the underground inflow while the output includes evapotranspiration, pumping and underground outflow. Groundwater balance is determined with the annual input and output quantities. For the groundwater budget calculation, choice of methods will depend on the spatial and temporal scale of investigation, characteristics of the aquifer, mechanism sought for understanding, availability of data of adequate quantity and quality, and spatial and temporal resolution of the

results (Flint *et al.* 2002; Heppner *et al.* 2007; Yin *et al.* 2011).

The main objectives of this study are to present the application of different methods, to compare the results of groundwater budget and evaluate methods applied in the Sandıklı basin. In this paper, the water-table fluctuation (WTF) method and meteorological water budget (MWB) were used to estimate the groundwater budget.

1.1 Description and conceptual modelling of the study area

Conceptual hydrological modelling is important for watershed management and it is the driving force behind many processes occurring on the watershed. In order to explain these processes in a water body (streams, lakes or groundwater), hydrologic and hydrogeologic relationships must be investigated and simulated. The conventional definition of groundwater conceptual modelling is mostly a qualitative and often pictorial description of the groundwater system, including a delineation of the hydrogeologic units, the system boundaries, inputs/outputs, and a description of the soils and sediments and their properties (Meyer and Gee 1999). According to Scanlon *et al.* (2002), the conceptual model describes location, timing, and likely mechanisms of recharge and provides initial estimates of recharge rates. A conceptual model is a narrative and graphical description of the characteristics of a site. The degree of details and accuracy of a conceptual model varies according to the hydrogeologic setting. A groundwater conceptual model has also been characterized as a hypothesis that describes the main features of the geology, hydrology and hydrogeochemistry of a site, as well as the relationships between these components and the patterns of flow (NAS 1996).

1.1.1 Geology and hydrogeology of the study area

Paleozoic, Mesozoic and Cenozoic aged rocks outcrop in the research area. In the study area, the basement rocks are quartzite, schist, limestone and dolomite of Precambrian and Paleozoic age. The basement rocks are overlain by sedimentary and volcanic rocks ranging from Mesozoic to Quaternary in age. The Seydişehir Formation is impermeable, and the Hüdai and Çaltepe formations are semi-permeable. The Akdağ Formation is permeable and disconformably overlies the previously mentioned units. At the top of the sequence, the Sandıklı Formation is semi-permeable, and lies above another disconformity. Clayey layers in the Pliocene lacustrine sediments are impermeable, but weakly cemented conglomerate and sandstone layers are permeable (Afşin 1997; Aksever 2011; Afşin *et al.* 2012).

Figure 2. Conceptual hydrogeological model of the basin.

Quaternary alluvium and Pliocene aged Hamamçay Formation are the main groundwater aquifers in the basin. The alluvium consists of sand, clay, gravel and silt levels and Hamamçay unit is composed of conglomerate having loose texture and sand levels are porous aquifers. The alluvium and Hamamçay Formation cover 174 and 366 km², respectively (figures 1, 2). The hydraulic conductivities of alluvium and Hamamçay Formation range from 1.03×10^0 to 9.25×10^{-2} m/day and from 1.02×10^0 to 9.60×10^{-2} m/day, respectively (Aksever 2011). These aquifers with similar lithological features were evaluated as a single porous aquifer. The results of well logs indicate that the thickness of the Quaternary and Pliocene units is between 200 and 300 m. The groundwater flow direction is towards NE in south of the basin, towards north in west of the basin and towards Kestel creek in north of the basin (figure 1). Average hydraulic gradients were measured between 9×10^{-4} and 0.01 respectively in these regions (Aksever 2011).

2. Methodology

Geological map of the study area is prepared with the help of Corel DRAW X4 software in 1:50,000

scale by utilizing the previous data and information. Annual rainfall has been measured at nine stations (Sincanlı, Sandıklı, Afyon, Hocalar, Şuhut, Haydarlı, Kızılören, Gümüşsu, Dinar) of the State Meteorology Works. The rainfall map of the basin was prepared using measured annual rainfall data with Isohyetal metod. Evaporatranspiration was determined with the Thornthwaite method (Thornthwaite and Mather 1957).

The flow of Kestel creek is measured in the streamflow gauging station which is located in Kızılca village and operated by State Hydraulic Works (SHW). For this study, groundwater head measurements were made in 22 piezometers during May 2007 and April 2010 (seven periods) in the alluvial aquifer. Then, the absolute altitudes were measured by means of a differential global positioning system (GPS). The hydraulic conductivity and transmissibility coefficients of the alluvial aquifer were determined using well pumping test results of SHW using Aquifer Test 4.0 Pro-software with Cooper-Jacob method. This involves the collection of pumping test data and subsequent calculations of different hydrogeological parameters. Water level measurements were used to determine the groundwater budget with the WTF method. Additional data including climatic, river discharge rates, and well production data were used in this

study to calculate the water budget of the Sandıklı basin with the MWB method.

3. Water budget calculations

Water budget is an accounting of the inflow to, outflow from, and storage within a hydraulic unit such as a basin or aquifer. This concept requires that a balance must exist between the total quantity of water entering and the total quantity of water going out in the basin. Under natural conditions and over long periods of time (before any development), groundwater recharge is balanced by groundwater discharge, i.e., Recharge = Discharge. As groundwater is nearly always moving, it will naturally flow from the recharge areas to the discharge areas. The discharge from the aquifers may occur in a variety of ways such as flow to streams, lakes, springs, water use, etc. (Sophocleous 2005).

Groundwater budget components are nearly impossible to measure directly and it must be quantified by indirect methods. It is difficult to estimate groundwater recharge and discharge reliably by one method because of uncertainties and assumptions associated with different methods (Yin *et al.* 2011). For this reason, it is commonly recommended that water budget should be estimated using multiple methods to constrain recharge estimates (Healy and Cook 2002; Scanlon *et al.* 2002; Misstear *et al.* 2009). In this study, the WTF and the MWB methods were used to estimate groundwater budget in the Sandıklı basin (Turkey).

3.1 Meteorological water budget method (MWB)

Simple meteorological water budget method (MWB) has been widely used for quantifying groundwater recharge. The MWB method is an integral component of any conceptual model of the system under study. The MWB method is a water balance equation. It is related to the inputs and outputs of a hydrologic system mathematically according to the law of conservation of mass. The water balance equation is given by:

$$\sum Q_{\text{in}} = \sum Q_{\text{out}} \quad (1)$$

Q_{in} : sum of all inflows over a period of time (groundwater recharge) and Q_{out} : sum of all outflows over a period of time (groundwater discharge).

3.1.1 Groundwater recharge

There are two recharge sources of the alluvial aquifer in the Sandıklı basin. These are:

- Infiltration from direct rainfall
- Infiltration from irrigation water

Rainfall: The most important source of recharge is the infiltration from direct rainfall. The rate of recharge from direct rainfall depends on the amount and duration of precipitation in the Sandıklı Basin. The isohyetal method (Linsley *et al.* 1975) was used to calculate the distribution of rainfall areas. Annual rainfall has been measured at nine stations (Şuhut, Dinar, Afyon, Sincanlı, Hocalar, Gümüşsu, Haydarlı, Kızılören, Sandıklı) of the State Meteorology Works (SHW) between 1975 and 2010. The rainfall map of the basin was prepared using measured annual rainfall data with isohyetal method (figure 3). Isohyetal method is considered as the most accurate method for computing mean rainfall. Rainfall gauges and locations are plotted and the contours of equal rainfall amounts (isohyets) are then drawn. The mean rainfall is calculated using the following formula.

$$P = \frac{\sum [A_n (P_n + P_{n+1}) / 2]}{\sum A_n} \quad (2)$$

where P_n are the isohyet values and A_n are the areas between isohyets.

The mean rainfall was calculated as 435.86 mm using this method. Recharge from average annual precipitation was calculated as $678.199 \times 10^6 \text{ m}^3/\text{year}$ in the Sandıklı basin which have 1556 km^2 watershed area.

Infiltration from irrigation water: Irrigation water for agricultural activities has been supplied from groundwater, a dam and three ponds in the basin. These dam and ponds are watering an area of 1859 hectares annually in the basin (SHW 2010). Irrigation from dam and ponds are provided via channels. All the irrigation water does not reach the root zone of the plants. Part of the water is lost during its transport through the channels and in the fields. The remaining part is stored in the root zone and eventually used by the plants. In other words, only part of the water is used efficiently, the rest of the water is lost for the crops on the fields that were to be irrigated. Therefore, irrigation efficiency should be known to calculate the amount of infiltration water from irrigation. Irrigation efficiency is a basic engineering term used in irrigation science to characterize performance of irrigation and evaluates use of irrigation water. This term depends on many factors that are related to the method of irrigation, soil hydraulic or infiltration characteristics, and hydraulic characteristics (pressure, flow rate, etc.) of the irrigation system (Howell 2003). Irrigation efficiency can be calculated with the following formula.

$$Ie = (Ec \times Ea) / 100 \quad (3)$$

Figure 3. Isohyet map of the investigation area.

where I_e is the irrigation efficiency, E_c is the conveyance efficiency (%), and E_a is the field application efficiency (%).

The conveyance efficiency mainly depends on the length of the channels, the soil type or permeability of the channel banks and condition of the channels. The indicative values of E_c for adequately maintained canals are determined by FAO according to the channel type, soil type and channel length (table 1). E_a mainly depends on the irrigation method and the level of farmer discipline. Some indicative values of the average E_a are given in table 2. Irrigation efficiency was calculated as 60% in the basin using these values and the above-

mentioned formula. In this case, 60% of irrigation water from the dam and ponds is used by vegetation and remainder 40% of water is percolated within underground and evaporated. Agricultural activities have been done on Pliocene Hamamçay Formation and Quaternary alluvium in the basin. The quantity of percolation from irrigation water to underground in these units is accepted as 15% due to clay and clayey gravel levels. Groundwater recharge via dam and these ponds was calculated as $1.27 \times 10^6 \text{ m}^3/\text{year}$.

In addition, most of the pumped water from wells in the basin is used for irrigation of agricultural lands. SHW (2010) estimate that more

Table 1. Indicative values of *Ec*.

Soil type	Earthen channels			Lined channels
	Sand	Loam	Clay	
Canal length				
Long (>2000 m)	60%	70%	80%	95%
Medium (200–2000 m)	70%	75%	85%	95%
Short (<200 m)	80%	85%	90%	95%

(http://www.fao.org/docrep/t7202e/t7202e08.htm)

Table 2. Indicative values of *Ea*.

Irrigation methods	Field application efficiency
Surface irrigation (border, furrow, basin)	60%
Sprinkler irrigation	75%
Drip irrigation	90%

(http://www.fao.org/docrep/t7202e/t7202e08.htm)

than 1150 wells exist in the plain area in the center of the Sandıklı Basin. Yield of these wells are between 4.78 and 51.10 l/s. Sprinkling method has been used in the agricultural lands of the Sandıklı basin. Irrigation efficiency was also calculated as 70% using indicative values and formula which are given by FAO. The amount of abstracted groundwater in the Sandıklı basin is $45.56 \times 10^6 \text{ m}^3/\text{year}$. The percolation quantity from irrigation water is accepted as 15%. Groundwater recharge from irrigation water via wells was calculated as $2.06 \times 10^6 \text{ m}^3/\text{year}$ in the basin.

3.1.2 Groundwater discharge

Evapotranspiration: The most important discharge component of groundwater in the study area is evapotranspiration. According to the meteorological data, the highest temperature in the study area occurs in August (it reaches 26.2°C), while the lowest value is in January (reaches -6.8°C). The Thornthwaite method (Thornthwaite and Mather 1957) is one of the most reliable and applicable, among the available water-budget methods (Scozzafava and Tallini 2001; Panagopoulos *et al.* 2002; Voudouris 2006). The Thornthwaite method is used to evaluate potential and actual evapotranspiration. The potential evapotranspiration (*Ep* in mm) is defined as the maximum obtainable value of evapotranspiration in wet-soil condition. The potential evapotranspiration (*Ep*) is calculated by the formula:

$$Ep(\text{mm}) = 16 (10t/I)^a \times p \quad (4)$$

where *t* is the monthly temperature ($^\circ\text{C}$) and *I* is the annual heat index.

$$I = \sum i \quad (5)$$

where *i* is the monthly heat index

$$i = (t/5)^{1.514}. \quad (6)$$

The coefficient *a* is given by the formula:

$$a = (675 \times 10^{-9} \times I^3) - (771 \times 10^{-7} \times I^2) + (178 \times 10^{-5} \times I) + 0.49239 \quad (7)$$

Multiplying the *Ep* values by one factor *p*, gives the corrected potential evapotranspiration (*Ep*). The actual evapotranspiration (*Eac*) was calculated according to relations between monthly potential evapotranspiration, monthly precipitation and water storage in the soil. In this method, averages of monthly precipitation and temperature data which are measured in Şuhut, Afyon and Dinar meteorological stations were used. Total average annual precipitation, potential and actual evapotranspiration were calculated as 428.36, 674.62 and 362.34 mm, respectively (table 3). The discharge with evapotranspiration in the Sandıklı Basin which has 1556 km^2 area was calculated as $563.801 \times 10^6 \text{ m}^3/\text{year}$.

Groundwater abstraction from wells: In the study area, groundwater has been abstracted from porous aquifer for irrigation and domestic purposes via approximately 1150 wells. The average annual yield of wells which are drilled on the alluvium and Hamamçay Formation is between 4 and 51 l/s (Aksever 2011). The average yield of a well is assumed to be 27 l/s to determine groundwater abstraction amount from wells in the basin. The total abstraction of groundwater is estimated to be based on 10 working hours per day and 75 days per year of wells. The total abstraction (*Qga*) by the

Table 3. Meteorological water budget calculated by Thornthwaite method.

	J	F	M	A	M	J	J	A	S	O	N	D	Total
<i>T</i> (°C)	1.0	1.9	5.5	10.0	14.5	18.8	21.9	21.6	17.3	12.1	6.6	2.7	134.1
<i>i</i>	0.1	0.2	1.1	2.9	5.0	7.4	9.4	9.2	6.6	3.8	1.5	0.4	47.7
<i>Ep</i> (mm)	1.9	4.5	19.5	44.5	79.0	109.7	134.1	123.0	82.9	48.9	20.1	6.5	674.6
<i>P</i> (mm)	41.5	36.9	44.0	54.9	46.2	30.8	20.9	16.8	14.8	33.6	41.8	49.0	428.4
<i>Eac</i> (mm)	1.9	4.5	19.5	44.5	79.0	100.3	20.9	16.8	14.8	33.6	20.1	6.5	362.3
<i>Ws</i> (mm)	100	100	100	100	69.5	0.0	0.0	0.0	0.0	0.0	21.7	64.1	
<i>Wsc</i> (mm)					−30.5	−69.5					21.3	42.5	
<i>Wsd</i> (mm)						9.4	113.2	106.2	68.1	15.3			312.3
<i>Wss</i> (mm)	39.6	32.5	24.5	10.4									107.1
<i>Ccl</i>	0.9	0.8	1.0	1.1	1.2	1.2	1.3	1.2	1.0	1.0	0.8	0.8	12.4

Note. *T*: temperature, *i*: heat index, *Ep*: potential evapotranspiration, *P*: rainfall, *Eac*: actual evapotranspiration, *WS*: water storage in the soil, *WSc*: change of water storage in the soil, *Wsd*: deficit of water storage in the soil, *Wss*: surplus of water storage in the soil, *Ccl*: correction coefficient of latitude (Şuhut, Afyon and Dinar meteorological stations were used in the method).

Table 4. Groundwater balance between the annual input and output quantities.

Recharge	($\times 10^6$) m ³ /year	Discharge	($\times 10^6$) m ³ /year
Rainfall	678.199	Evapotranspiration	563.801
Infiltration from irrigation water (ponds)	1.27	Abstraction from wells	45.56
Infiltration from irrigation water with (wells)	2.06	Run-off	12.24
Total	681.529	Total	621.601
Difference	59.928 $\times 10^6$ m ³ /year		

1150 wells was calculated as 45.56×10^6 m³/year using formula (8).

$$Q_{ga} \text{ (m}^3/\text{s)} = Q_{wy} \times Th \times Td \times Wn \quad (8)$$

where Q_{wy} is the average yield of a well (m³/s), Th is hours worked per day of a well (s), Td is days worked per year of a well, and Wn is the total number of wells.

Surface water run-off: Kestel creek is an important surface water run-off in the Sandıklı Basin. It discharges to Büyük Menderes river which is located outside the basin. The surface run-off from the Kestel creek has been measured using universal flow meter at a gauging station by SHW. According to the data which are measured in the 1986–2010 period, the average annual discharge from Kestel creek was calculated as 12.24×10^6 m³/year.

Groundwater balance: The groundwater balance equation of the study area is given by equation (9):

$$Rr + Rip + Riw = Et + Q_{ga} + Q_{sur} \quad (9)$$

where Rr is the recharge from rainfall, Rip is the infiltration from irrigation water (ponds), Riw is the infiltration from irrigation water with (wells),

Et is the Evapotranspiration, Q_{ga} is the total abstraction from wells, and Q_{sur} is the surface run-off from the Kestel creek.

The meteorological groundwater budget of the study area is summarized in table 4. The hydrologic budget goes towards the positive trend (59.928×10^6 m³/year), when the input values reach 681.529×10^6 m³/year which is greater than the output which was calculated as 621.601×10^6 m³/year (table 4). The contribution of evapotranspiration to the total discharge rate is approximately 90% and the contribution of rainfall to the total recharge rate is also approximately 99% in this budget. 42.10×10^6 m³/year which is equal to 70% of the differences between total recharge and discharge was estimated as annual reserve storage in the basin considering the probable errors made in calculations and measurements.

3.2 Water table fluctuation method (WTF)

The water level fluctuates primarily in response to variation in recharge and discharge rates. The fluctuations are reflected by the water level changes in wells in response to the changes in groundwater storage. The groundwater table starts to rise during July to September period due to an increase in infiltration from precipitation. Water-table fluctuation (WTF) method evaluates changes in groundwater. It is somewhat surprising that

relatively few methods for estimating groundwater recharge include an analysis of groundwater level fluctuations, although groundwater levels are the only directly measurable result of recharge. The WTF method is straightforward, easy to apply, and makes use of directly measurable data. Furthermore, the WTF method directly involves the result of the groundwater recharge process, unlike many of the methods concerned with unsaturated processes (Jie *et al.* 2011). Methods for estimating groundwater recharge from groundwater level time series were first applied in the 1920s (Meinzer

1923; Meinzer and Stearns 1929). However, this method was modified by several researchers in different years (Sophocleous 1991; Ketchum *et al.* 2000). Nowadays, the WTF method presented by Healy and Cook (2002) is the most widely used method. This method is based on the premise that rises in groundwater levels in unconfined aquifers are due to recharge water arriving at the water table. In other words, volume change of groundwater in an aquifer is calculated from the groundwater level changes. Difficulties in applying the method are related to determining specific yield and

Figure 4. 2007–2008 term groundwater level fluctuation map.

groundwater level decrease (Scanlon *et al.* 2002; Moon *et al.* 2004; Crosbie *et al.* 2005; Jie *et al.* 2011). Other limitations of the WTF method are given as regionalizing results may significantly reduce the accuracy of the calculated recharge because groundwater level fluctuations measured in a well are only representative for a small area of a heterogeneous aquifer and WTF methods can only be used for shallow, unconfined aquifers (Healy and Cook 2002; Jie *et al.* 2011).

In the WTF method, recharge (R) calculates a given time interval (Δt) as the potential

groundwater rise (Δh) multiplied by the specific yield (Sy) in equation (10) (Healy and Cook 2002).

$$R = \frac{(Sy \times \Delta h)}{\Delta t}. \quad (10)$$

Specific yield is in fact a function of media porosity, depth of the water table, drainage duration, etc. The parameter is difficult to measure, and there is no efficient or widely accepted method for deriving it from other data (Jie *et al.* 2011). Effective porosity is often equated to the specific yield of the porous material or assumed that the volume

Figure 5. 2008–2009 term groundwater level fluctuation map.

of water in the pore space can be freely drained by gravity due to the change in the hydraulic head (Kresic and Stevanovic 2009). The effective porosity and specific yield is accepted as equal in most practical field applications (Kasenow 2001).

A detailed description of each step which are performed in this study is presented below:

Step 1: Groundwater levels were measured in May 2007–April 2010, at seven periods and matches according to the static conditions in the geographic

basin. The groundwater level is between 0.43 and 25.7 m in the basin.

Step 2: According to the variation of groundwater level, groundwater level fluctuation maps for 2007–2008, 2008–2009 and 2009–2010 periods were prepared (figures 4, 5, 6). These maps are divided into zones which have iso-level exchange. These zones were classified as I zone (0–3 m), II zone (3–6 m), III zone (6–9 m) and IV zone (>9). The areas of each zone on these maps were calculated.

Figure 6. 2009–2010 term groundwater level fluctuation map.

Step 3: In this study, recharge (R) was estimated using groundwater rise and effective porosity values considering WTF method approach. Unlike WTF method, R was calculated using formula of volume change which was presented by Castany (1963).

$$R = A \times \Delta h \times n_e \quad (11)$$

where A is the area of each zone, Δh is the groundwater rise and n_e is the effective porosity of each zone.

Step 4: The effective porosity (n_e) was determined using hydraulic conductivity (k) values of aquifer with equation (12) developed by Marotz (1968).

$$n_e = 0.462 + 0.045 \ln k. \quad (12)$$

The values of hydraulic conductivity (k) were calculated with Cooper–Jacob time method using Aquifer Test 3.5 software by pumping tests results of 50 wells in the study area.

Step 5: The groundwater recharges for each zone were calculated using equation (11) and these results were given in table 5.

Step 6: The groundwater potentials (dynamic reserves) in 2007–2008, 2008–2009 and 2009–2010 periods were estimated with the sum of the groundwater recharges for each zone (table 5). These were calculated as 62.82×10^6 , 53.58×10^6 and 48.52×10^6

m^3/year for 2007–2008, 2008–2009 and 2009–2010 terms, respectively.

According to these calculations, average groundwater budget of the study area were calculated as $54.97 \times 10^6 \text{ m}^3/\text{year}$. $38.48 \times 10^6 \text{ m}^3/\text{year}$ which is equal to 70% of the differences between total recharge and discharge was estimated as annual reserve storage in the basin considering the probable errors made in calculations and measurements.

4. Sustainable usage

The sustainability of groundwater utilization must be assessed from an interdisciplinary perspective, where hydrology, hydrogeology, ecology and climatology play an important role. Groundwater basins should be considered as a whole hydrologic system which takes into consideration conceptual hydrogeological modelling of the basin. The integration of geological, hydrogeological and hydrological data is required in order to safely manage the groundwater resources in a given basin. Estimation of groundwater quantity is one of the important parameters to assure sustainability of groundwater basins. Sustainability studies require a balance of the entire hydrologic system, not just of the aquifer. So, sustainability of groundwater resources require catchment and aquifer

Table 5. *Dynamic groundwater reserve according to the groundwater level fluctuations.*

Zones	Effective porosity (n_e)	Area (km^2)	Groundwater level change (m)	Hydraulic conductivity ($k\text{-m/s}$)	Groundwater reserve (Rn_e) (m^3/year)
2007–2008					
I	0.022	224.01	1.47	2.1×10^{-5}	7.24×10^6
II	0.053	159.61	3.85	0.1×10^{-4}	32.57×10^6
III	0.023	98.72	6.55	2.1×10^{-5}	14.87×10^6
IV	0.02	19.65	20.70	4.0×10^{-6}	8.14×10^6
				Total	62.82×10^6
2008–2009					
I	0.002	197.16	1.65	2.3×10^{-5}	0.65×10^6
II	0.013	7.14	4.86	1.9×10^{-6}	0.45×10^6
III	0.036	60.54	7.80	0.8×10^{-5}	17.0×10^6
IV	0.011	237.14	13.60	4.5×10^{-5}	35.48×10^6
				Total	53.58×10^6
2009–2010					
I	0.003	187.16	1.00	3.3×10^{-5}	0.56×10^6
II	0.015	18.28	4.86	4.8×10^{-5}	1.33×10^6
III	0.007	182.03	7.20	4.1×10^{-5}	9.17×10^6
IV	0.02	114.53	16.35	1.5×10^{-5}	37.45×10^6
				Total	48.52×10^6
Terms		Groundwater reserve (m^3/year)			
2007–2008		62.82×10^6			
2008–2009		53.58×10^6			
2009–2010		48.52×10^6			
Average		54.97×10^6

Figure 7. Changes in groundwater levels at the porous aquifer.

Table 6. Groundwater drawdown in the basin.

No.	Period	Number of pumping wells	Minimum (m)	Maximum (m)	Mean (m)	Median (m)
1	2007–2008	22	0.43	18.81	9.62	2.43
2	2008–2009	22	0.37	21.53	10.95	8.58
3	2009–2010	22	0.32	25.70	13.01	15.00

management plans that clearly integrate groundwater and surface water systems. This requires an accurate catchment and aquifer water balance to develop management plans which recognize the long timeframes of aquifer and catchment interaction. Development of area-specific groundwater management plans requires an understanding of geology, hydrogeological settings, hydrodynamics, environmental water requirements, historical water use practices and local water use, present and future. Therefore, groundwater budget calculations related to conceptual hydrogeological modelling of a basin are inevitable for groundwater basins.

In the Sandıklı Basin, groundwater level is decreased each year due to excessive groundwater withdrawals for irrigation. The groundwater drawdown is between 2.43 and 15.00 m approximately according to groundwater level measurements which are made at 22 wells for three periods (2007, 2008 and 2009) in the study area (Aksever 2011; figure 7; table 6). Therefore, sustainable groundwater use is under serious crisis due to the rapid depletion of groundwater caused mainly by pumping for agricultural irrigation in the basin. In the long term, it is impossible to extract more water from an aquifer than is recharged with infiltration from precipitation in the basin. Sooner or later, the pumping rates will automatically have to be adjusted according to the availability of water. The key steps to move towards sustainable use of

groundwater in the basin are basic and commonsensical, but a sustainable groundwater management strategy can only be as good as its potential for implementation. The following steps were outlined for the basin.

- *Improve the knowledge base:* Our ability to effectively manage groundwater is hampered by gaps in our knowledge of the groundwater resource, including recharge rates and mechanisms, and the linkages between groundwater and surface water systems (Sophocleous 2005). Therefore, the number of current wells must be known to determine the total abstraction from wells and boreholes in the basin. The number of wells which does not have legal permission should be identified and should be controlled. In addition, the current knowledge related to well and boreholes such as yield, depth, working hour and the number of working days should be updated. Knowledge on aquifers such as permeability, transmissibility, specific yield, storage and groundwater quality should be identified for sustainable usage of aquifer.
- *Search for new water sources:* Alternatively, surface water sources should be investigated, especially for irrigation water in the basin.
- *Improve water efficiency and crop productivity:* Achieving sustainable groundwater use requires that everyone uses water as efficiently as possible.

This means removing the incentives to waste water, and providing incentives to conserve it. The performance of irrigation system should be improved in the basin. Irrigation efficiency is a critical measure of irrigation performance in terms of the water required to irrigate a field, farm, basin, irrigation district, or an entire watershed. The enhanced understanding of irrigation efficiency can improve the beneficial use of limited and declining water resources needed to enhance crop and food production from irrigated lands.

- *Revise crop type*: Potato is grown in about 80% of total cultivated area in the basin. Compared with other crops, production of potato requires excessive water. Potato cultivation caused decrease of groundwater level in Kusura and Emirhisar villages. Therefore, the crop type should be changed, and crop types which do not require excessive water should be selected in the basin.
- *Improve public education and understand better public's attitudinal motivations*: Increasing education of the public on water issues and promoting awareness of water-efficient technologies should be a permanent goal of water management. The need for education cannot be overstated: sustainable groundwater use cannot be achieved without awareness and involved citizenry. That is why improvements in reporting and public access to information are so important (Sophocleous 2005).
- *Adopt a goal of sustainable use*: In order to avoid or reduce the severe ecological, social, and economic impacts of groundwater mining, we need to adopt as a management goal, the long-term sustainability of groundwater resources (Sophocleous 2005). Therefore, a management plan for water sources must be developed in the basin. Considering the current situation of groundwater levels in the basin, drilling of new wells should be restricted, abstraction of groundwater from existing wells should be controlled and effective usage of groundwater should be improved.

5. Discussion and conclusion

Nowadays, the most important problem is decreasing of water quantity due to unplanned usage with growing need of water in the groundwater aquifers. The sustainable management of the natural groundwater resources in semi-arid and arid areas requires a detailed understanding of the regional hydrological and hydrogeological processes. The groundwater balance of a catchment and the processes of recharge, storage, evapotranspiration loss and discharge can be described by simple but physically based conceptual model components. Correct

determination of the groundwater budget in a basin is associated with selection of suitable budget calculation method as well as the associated understanding of the regional hydrological and hydrogeological processes in detail. It is difficult to estimate water budget reliably by a single method because of uncertainties and assumptions associated with different methods. For this reason, it is commonly recommended that water budget should be estimated using multiple methods.

The MWB method is widely used to determine the groundwater budget of a catchment. Meteorological water budget (MWb) method may also have fairly high uncertainties, but these uncertainties are repairable with well-known conceptual hydrogeological model in the study area. The reliability of the water-balance method depends to a large extent on how accurately the values of the variables in the water-balance equation can be measured or estimated. Groundwater techniques generally provide information on actual recharge, because water has reached the water table. The WTF method is attractive because groundwater-level observations are often available; the method can also give information on temporal and areal recharge variations. However, this method can be misleading if the water-level fluctuations are confused with those resulting from pumping, barometric, or other causes.

In this study, MWB method was applied to determine the groundwater budget in the Sandıklı Basin. The WTF method was used to control the result of MWB method. These methods have different approaches and different time scales were used in these methods. 30 years (1975–2010) of records (precipitation, temperature, flow, etc.) were used in the MWB method. Groundwater levels which are used in the WTF method were measured between 2007 and 2010. The average groundwater budget of the study area was calculated as 42.10×10^6 m³/year with the MWB method and it was also calculated as 38.48×10^6 m³/year with the WTF method. It is shown that, if conceptual hydrogeological modelling of the basins is well-known and reliable data are obtained, the MWB method gives accurate results in basins. Nevertheless, comparison of multiple methods is found to be valuable for determining the plausible budget amount and for highlighting the uncertainty of the estimates.

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