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Estimating Regional Groundwater Recharge Using a Hydrological Budget Method

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Abstract Estimating groundwater recharge is a key component in determining the sustainable yield of groundwater resources in arid and semi-arid areas such as southern California. Estimating groundwater recharge on a regional scale requires developing a water budget that incorporates data on boundary conditions, aquifer properties, groundwater levels, and groundwater production. The hydrological budget method proposed herein is simple, cost-effective, and easy to apply. It utilizes matched pairs of groundwater level measurements, groundwater extraction data, and distributed specific yield information for estimating groundwater recharge. In this method, ARCGIS 9.0 Geostatistical and Spatial Analyst applications are used for interpolating/extrapolating and creating grids for specific yield, bedrock elevation, and raw groundwater data. The annual average groundwater recharge for the Hemet subbasin in western Riverside County, California, from 1997 to 2005 is estimated at 12.5 MCM, with wet and dry periods ranging between 14.9 MCM and 11.7 MCM, respectively. The proposed method utilizes information commonly available

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to most groundwater management entities, such as groundwater production data, groundwater level measurements, and lithologic information.

Keywords Groundwater recharge · Water budget · GIS · Hemet subbasin

1 Introduction

Estimating groundwater recharge is a key component in determining the sustainable yield of groundwater resources in arid and semi-arid regions. Groundwater resources management requires estimating groundwater recharge on large spatial and temporal scales; while detailed information on groundwater recharge is required for site-specific studies and short time frames for assessing groundwater contamination. 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). There are many methods available for estimating saturated groundwater recharge. However, the amount of information that is needed depends on the complexity of the method. For example, some methods require extensive fieldwork, while others involve development of complex mathematical models. Methods for estimating groundwater recharge are subdivided into different types based on the hydrologic sources from which data are obtained (namely, surface water and the unsaturated and saturated zones); however, this subdivision is arbitrary and probably not ideal (Scanlon et al. 2002). In general, the major methods for estimating saturated groundwater recharge are tracer techniques, numerical models, and hydrological budgets. Tracer techniques involve injecting a tracer, such as Tritium $^{3-}$H, into the groundwater at a specified depth in the unsaturated zone of the soil column, and studying the vertical movement of the tracer during the next hydrologic cycle (Athavale and Rangarajan 1990). Tracer techniques are widely used in arid and semi-arid regions to estimate groundwater recharge from precipitation and irrigation; however, they do not measure water flow directly, which may cause an over- or under-estimation of recharge (Lerner et al. 1990).

Groundwater numerical flow models can be used to estimate groundwater recharge. The recharge flux can be obtained from the calibration process, or the model can be used to calculate the recharge that is necessary to match target heads (Stoertz and Bradbury 1989; Cherkauer and McKereghan 1991; Cherkauer 2004; Said et al. 2005). It is important to note that groundwater numerical flow models do not generate unique solutions for hydraulic heads, because the solutions depend on how well the aquifer structure and boundary conditions are described, as well as the accuracy of descriptions of aquifer properties such as hydraulic conductivity. In addition, developing groundwater numerical flow models is costly, requires extensive historical data, is time consuming, and requires modeling expertise.

The hydrological budget method is widely used by hydrologists for estimating soil moisture budgets, river channel budgets, and saturated groundwater recharge. The hydrologic budget method accounts for all inflow and outflow, as well as storage changes in the unsaturated and saturated zones. For example, for calculating saturated groundwater storage changes, inflows (percentages of precipitation, surface flow, irrigation returns, percolation from storage ponds, and subsurface inflow), and outflows (evaporation, consumptive use, and subsurface outflow) are estimated, and a single value for the specific yield is assumed. The specific yield parameter is used in calculating the drained/obtained water volume from saturated storage due to changes in groundwater levels. Determining a single representative value for specific yield limits the usefulness of the watertable fluctuation method for estimating groundwater recharge (Scanlon et al. 2002). In general, using the hydrologic budget method for estimating groundwater recharge is not accurate due to:

1. difficulties in determining parameters such as evapotranspiration, runoff, intercepted precipitation by vegetation, groundwater baseflow, and boundary flow;
2. difficulties in determining relationships for unsaturated zone parameters such as effective hydraulic conductivity and moisture content because of the complicated nature of the unsaturated flow system; and
3. the use of a single value for specific yield for quantifying drained water volume due to changes in groundwater levels.

Geographical Information Systems (GIS) have been used in modeling groundwater for resources management, including groundwater recharge. Thematic layers for slope, infiltration rate, depth to groundwater, alluvial sediments, and land use were integrated into the GIS environment by the means of Boolean and Fuzzy logic to identify preferred artificial groundwater sites in the Gavbandi Drainage Basin in the southern part of Iran (Ghayoumian et al. 2006). Extensive hydrogeological survey exploration required for characterizing groundwater conditions was replaced by integrating remote sensing data into a GIS environment to identify suitable sites for groundwater recharge in hard rock areas in part of the Vidisha District in India (Saraf and Choudury 1998).

The purpose of this paper is to present a simple hydrologic budget method for estimating groundwater recharge using input parameters that are readily available or obtainable and accurately measured such as groundwater levels and extraction and the aerial distribution of specific yield for quantifying saturated groundwater storage changes.

2 Methodology

In this study, groundwater recharge is defined as the residual of waters applied on the ground surface that pass through the unsaturated zone and reach the saturated groundwater system. Applied water sources result from precipitation, irrigation, man-made storage ponds, river or stream flow, and any other recharge source. The hydrologic budget for a geographic basin can be written as:

$$(W + Q_{\mathrm{in}}) - (\mathrm{ET} + \mathrm{RO} + \mathrm{IP} + Q_{\mathrm{bf}} + Q_{\mathrm{out}}) - Q_{\mathrm{w}} = \pm \Delta S \tag{1}$$

Where W is the applied water on the ground surface; Q_{in} and Q_{out} are subsurface water fluxes into and out of a geographic basin along a boundary; ET represents evapotranspiration losses in surface and subsurface waters, including the unsaturated and saturated zones; RO is surface water runoff; IP is intercepted precipitation by vegetation; Q_{bf} is groundwater discharge to streams (baseflow); Q_{w} is groundwater withdrawal through pumping wells; and ΔS is the change in saturated groundwater storage. Equation 1 does not include unsaturated storage changes, because of its insensitivity to the mechanism by which water moves through the unsaturated zone

(Healy and Cook 2002). The units for all components in the hydrologic budget equation are in volume per time period. Estimating values for the individual variables involved in the hydrologic budget, such as evapotranspiration, groundwater baseflow, runoff, intercepted precipitation, and others can be problematic. In order to avoid difficulties in estimating these variables, the differences between total applied water and water losses, other than via the subsurface to adjacent basins, can be lumped into a single term - groundwater recharge. As mentioned before, groundwater recharge includes any percolated water that reaches the saturated portion of the watertable aquifer per time period, and can be written as:

$$R_{\mathrm{t}} = \{W - (\mathrm{ET} + \mathrm{RO} + \mathrm{IP} + Q_{\mathrm{bf}})\} \tag{2}$$

Where R_{t} is groundwater recharge. Net subsurface groundwater recharge along the geographic basin boundary, $(Q_{\mathrm{in}} - Q_{\mathrm{out}})$, can be added to the net groundwater recharge term, Eq. 2, without significant changes in the hydrologic budget, since net subsurface groundwater recharge eventually contributes to the saturated groundwater system. Therefore, Eq. 2 can be modified with the following result:

$$R_{\mathrm{t}} = \{W - (\mathrm{ET} + \mathrm{RO} + \mathrm{IP} + Q_{\mathrm{bf}}) + (Q_{\mathrm{in}} - Q_{\mathrm{out}})\} \tag{3}$$

Assuming watertable aquifer conditions, the change in groundwater storage per time period can be written (Bredehoeft et al. 1982) as:

$$\Delta S = \pm \Delta H \times A_{\mathrm{gb}} \times \mathrm{SY} \tag{4}$$

Where ΔH is the average change of the measured groundwater levels per time period; A_{gb} is the area of the geographic basin; and SY is the average specific yield of the watertable aquifer.

Fluctuation of groundwater levels can be used to estimate the groundwater recharge rate in an unconfined aquifer for wet and dry seasons (Rasmussen and Andreasen 1959; Healy and Cook 2002). The first authors developed a water budget equation that includes precipitation, evaporation, runoff, and change in groundwater storage. The change in groundwater storage is calculated by multiplying the specific yield and the changes in groundwater level. Healy and Cook (2002) pointed out that changes in groundwater storage can be attributed to recharge and groundwater flow into the basin minus baseflow, evapotranspiration from groundwater, and groundwater flow out of the basin. The groundwater recharge rate per time is calculated by multiplying the specific yield and the changes in groundwater level.

Substituting Eqs. 3 and 4 into Eq. 1 and simplifying results in:

$$R_{\mathrm{t}} = Q_{\mathrm{w}} \pm \left(\Delta \mathrm{H} \times \mathrm{A}_{\mathrm{gb}} \times \mathrm{SY}\right) \tag{5}$$

If the geographic basin area is divided into grids, then the groundwater recharge per time period, R_{t}, equals the summation of groundwater recharge of each grid, and can be presented as:

$$R_{\mathrm{t}} = \sum_{i=1}^{i=n} r_i = Q_{\mathrm{w}} \pm \sum_{i=1}^{i=n} \left(\Delta h_i \times a_i \times \mathrm{sy}_i\right) \tag{6}$$

Where r_i, Δh_i, a_i, n and sy_i represent the groundwater recharge, the change in groundwater level between two time periods, the area, the number of grids, and the specific yield for a grid, respectively. The effect of groundwater withdrawal is assumed to be equally distributed on the grids. Any time period may be used—a month, 3 months, or 1 year. However, for semi-arid regions where groundwater levels are very deep, it is best to assume longer time period because of the lag time necessary for groundwater recharge to reach the saturated watertable system (Fig. 1). The groundwater storage change equations, Eq. 4 for example, can be applied over longer time intervals such as seasonal or annual to produce an estimate of change in subsurface storage (Healy and Cook 2002). In this study, a 1-year time period was used, which covered the period between the spring of the first year and spring of the following year. In the hydrologic budget, Eq. 6, only matched pairs of groundwater level measurements from the same well for a quasi-static condition are used to create geographic surfaces for groundwater. In addition, if more than one water level measurement is available per well in the same time frame, the measurements are averaged to provide a single value. Quasi-static conditions usually occur during the spring time (January through April) of each year, when groundwater extractions are low compared to other times during the year. The proposed hydrologic budget method is easy to use and requires only a few parameters that are readily available for most basins, such as groundwater extraction and measured water level data. The specific yield depends on the physical properties of porous materials of the aquifer as well as on factors such as entrapped air near the watertable, stratification of materials above the watertable, watertable position, and the rate of change in watertable elevation (McWhorter and Sunada 1988). Specific yield is defined as the volume of water that an unconfined aquifer releases from storage per unit of surface area of aquifer per unit of decline in the watertable (Freeze and Cherry 1997). The specific yield must be determined in order to estimate the available and obtainable water supply from an aquifer for an increase or decrease in groundwater levels (Johnson 1967). Determining a representative value for specific yield is difficult because of the heterogeneous nature of porous aquifer materials. By assuming a single value for specific yield, groundwater recharge is usually overestimated (Sophocleous 1985).

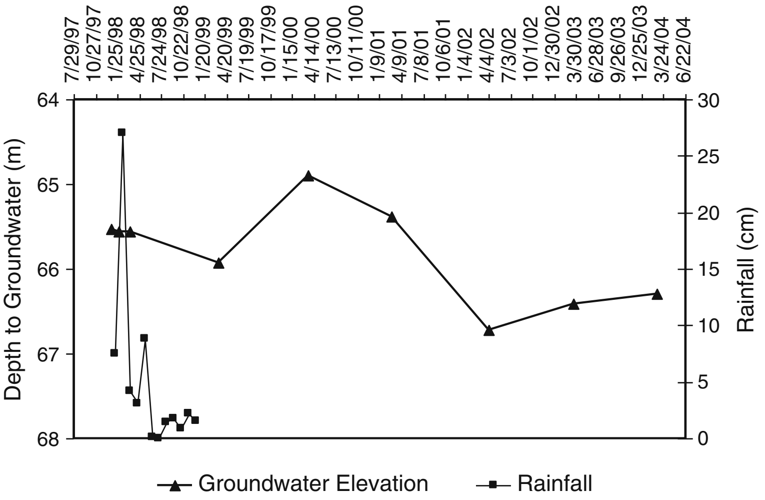


Fig. 1 Precipitation recharge impacts on groundwater levels of the dairy north well, Hemet Subbasin

Methods for determining specific yield include the analysis of time-drawdown data from pumping tests; water-balance calculations based on the measured fluctuations of the watertable in response to given rates of recharge and discharge; laboratory drainage experiments on samples of aquifer material; and parameter estimation by means of numerical models (Neuman 1988). Lithologic logs offer descriptive information on the porous materials along the drilled depths of wells and include a description of soil types, such as silt with siltstone, silt and sand, silt and sand and gravel, clay with gravel, and sand with gravel, to name a few. In addition, lithologic descriptions recorded during the installation of wells and boreholes can be used to create an aerial distribution for specific yield within a geographic basin. In this study, lithologic information from drillers' logs was used for calculating average specific yield for soil mixture combinations for depths of groundwater level decline. Specific yield values were assigned for different soil mixture combinations using documented data obtained from field and laboratory tests (McWhorter and Sunada 1988; Johnson 1967) as well as personal experience based on pumping tests, groundwater production, and other factors. For example, the specific yield values for the soil mixture combinations of "sand and gravel with slit", "sand with gravel and silt", "gravel and sand with slit", and "gravel with sand and silt" were estimated to be 0.12, 0.15, 0.1, and 0.07, respectively. In this effort, specific yield values were assigned to 179 soil mixture combinations, and samples of the values are shown in Table 1. A simple Visual Basic Program called Well Tool (WET) was developed for calculating average values for the specific yield for a defined depth of the watertable aquifer. The formula used for calculating average specific yield was:

$$\mathrm{sy}_{\mathrm{avg}} = \frac{\sum_{j=1}^{j=m} b_j \times \mathrm{sy}_j}{\sum_{j=1}^{j=m} b_j} \tag{7}$$

Where $\mathrm{sy}_{\mathrm{avg}}$ is the average specific yield for different soil materials that are included in a specified depth of watertable aquifer; sy_j is the specific yield value for a specific soil mixture combination; m is the number of soil materials in the specified depth and b_j is the depth of a soil mixture combination. The WET program reads depths of

Table 1 Samples of specific yield values for various soil types

Soil description	Specific yield
Sand	0.20
Sand and gravel	0.20
Gravel	0.15
Sand with gravel and silt	0.15
Silty sand and gravel	0.12
Sand with silt	0.12
Sand and gravel with clay	0.10
Sand, silt, and gravel	0.10
Sand and gravel with clayey silt	0.07
Sandy silt and clay	0.05
Cemented sand, clay and gravel	0.05
Silt	0.03
Clay	0.01

soil mixture combinations that are available in the lithologic information, and then assigns values for specific yield using the information in Table 1.

The specific yield values assigned for different combinations of soil textures are based on laboratory analyses (Johnson 1967), pumping tests, and on personal experience in the San Jacinto Watershed that included groundwater studies and exploration. The specific yield for different combinations of soil textures for groundwater declines/increases was estimated using average approach (Eq. 7). This average approach was used by (McWhorter and Sunada 1988) for estimating hydraulic conductivity for stratifications.

The reliability of the proposed hydrologic budget method depends on the accuracy of the measured input components such as groundwater levels and groundwater withdrawal, and the estimated specific yield based on lithologic descriptions. Groundwater levels can be accurately measured using devices such as electric sounders. Also, groundwater extraction can be recorded accurately using meters on production wells. In addition, the proposed hydrologic budget method captures the variations in the porous aquifer materials along aquifer depths as well as across the geographic basin. The method uses spatial distribution of the specific yield values obtained from lithologic information for quantifying changes in groundwater volume instead of using a single value for specific yield.

3 Case Study

The proposed hydrologic budget method was used for estimating annual groundwater recharge in the Hemet subbasin. The Hemet subbasin is within the San Jacinto Watershed, located in western Riverside County in southern California, (Fig. 2). The area of the Hemet subbasin is 12,500 hectares. The Casa Loma Fault defines the eastern boundary of the Hemet subbasin and is generally considered an impermeable barrier to groundwater flow, although leakage across the fault may occur locally in some areas. The Perris South and Lakeview subbasins define the western and northern boundaries of the Hemet subbasin. Diamond Valley Lake (DVL), a drinking water reservoir, is located southwest of the Hemet subbasin; its maximum capacity is 987.0 MCM. Flow of State Project Water into the reservoir began in November 1999 and it was filled by early 2002 (Metropolitan Water District of Southern California 2005). Several recycled water storage ponds are located in the northern part of the Hemet subbasin (Fig. 2). The maximum storage capacity of these ponds is estimated at 1.0 MCM, and the average percolation rate of the ponds is estimated to be 1.6 cm per day. The annual average temperature in the region is 20 Celsius. The annual average precipitation in the Hemet subbasin is 33.5 cm and most of the rain falls during October through April. The main sources for irrigation are groundwater and recycled water. The bedrock depth for the Hemet subbasin can range up to 390 m below ground surface; water-bearing materials include interbedded and inter-mixed deposits of sand, gravel, silt, clay, cobbles, and boulders (TechLink Environmental, Inc. 2002). The aquifer underlying the Hemet subbasin is assumed to be an unconfined aquifer. Groundwater levels in the Hemet subbasin have experienced a steady decline as a result of increasing groundwater extraction for domestic and agricultural irrigation purposes (Fig. 3).

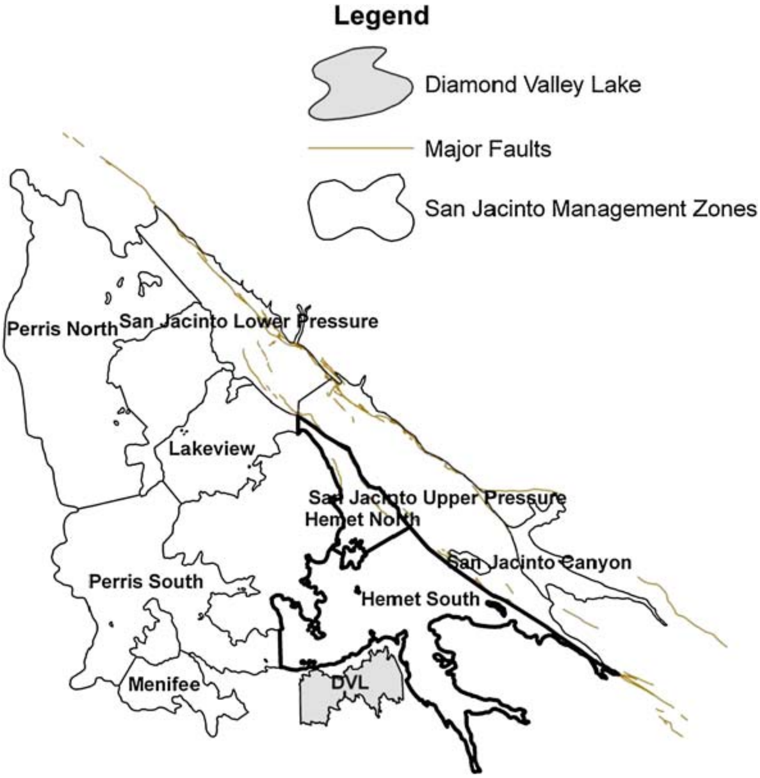


Fig. 2 San Jacinto Watershed Subbasins

Estimated groundwater recharge for the Hemet subbasin was analyzed for the 8-year period from 1997 to 2005. This timeframe was selected because matched pairs of groundwater level measurements were available, and because the period between spring 1997 and spring 2005 contains two wet years—1998 and 2005—with annual precipitation of 58.9 and 62.9 cm, respectively. Forty-two observation wells with matched pairs of water level measurements were used in the groundwater recharge analysis, and their distribution in the Hemet subbasin was uniform (Fig. 4).

Groundwater level measurements were recorded twice a year, once during spring and once during the fall. Groundwater conditions in the spring of each year were assumed to be quasi-static, because groundwater withdrawal is low during that time of year and represents less than twenty percent of the total annual groundwater withdrawal. The groundwater withdrawal, Q_w, in the hydrologic budget includes all groundwater extracted between May 1st and April 30th of the following year. The following steps describe the procedures used to calculate saturated groundwater recharge for the Hemet subbasin for two consecutive years using ArcGIS products:

Step 1 Create a polygon shape file for the Hemet subbasin, and add it to the ArcMap project.

Step 2 Create a point shape file for the Hemet subbasin bedrock, and add it to the ArcMap project.

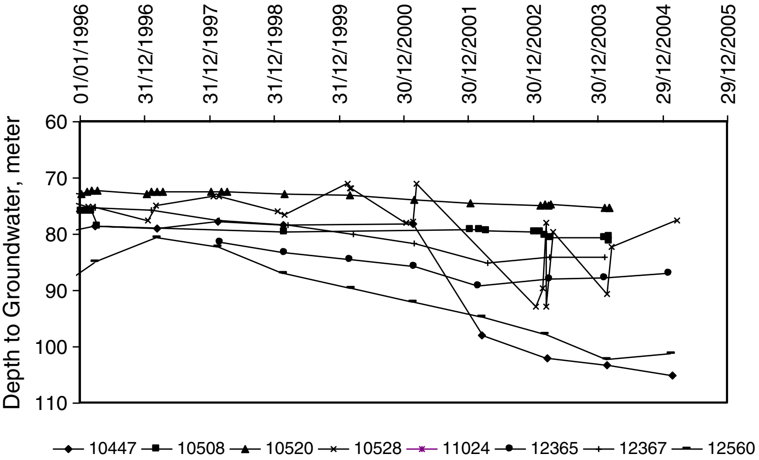
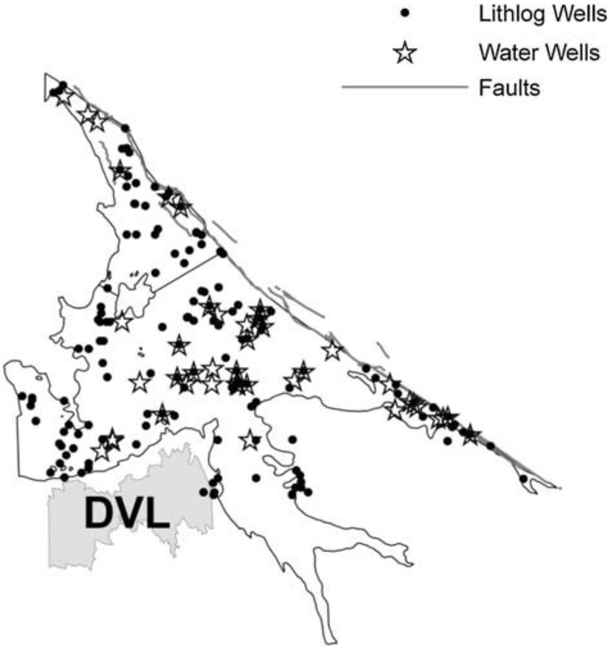


Fig. 3 Depth to groundwater at different locations for the Hemet Subbasin wells

Step 3 Calculate arithmetic averages for the groundwater levels for each year starting with 1997.

Step 4 Run the WET program to extract the specific yield values for each of the driller's logs within the water level change zone of two consecutive years.

Fig. 4 Distribution of observation and lithlog wells in the Hemet Subbasin



The WET program will calculate the average specific yield for soil materials located within the water level change zone.

Step 5 Create a point shape file for the specific yield data, and add it to the ArcMap project.

Step 6 Create point shape files for the groundwater level measurements for spring of the first year and for spring of the second year, and add them to the ArcMap project.

Step 7 Use ArcGIS 9.0 Geostatistical Analyst to create 150.0 by 150.0 m grids for the Hemet subbasin. The Geostatistical Analyst uses groundwater level measurements, specific yield, and bedrock raw data to assign values to grids. Use the Kriging Method for interpolation because the Mean and the Root Mean Square errors are small when compared to using other methods in the Geostatistical Analyst. Export the generated grid values to an Excel spreadsheet for calculating saturated groundwater recharge between two consecutive years. The Excel spreadsheet is designed to include four fields for each grid for each year; these fields are (1) estimated groundwater level, (2) estimated specific yield, (3) estimated bedrock elevation, and (4) calculated water volume for that grid. The groundwater grid volume is calculated as the difference between the groundwater level and the bedrock elevation times the grid area and the specific yield. However, the groundwater volume should be assumed to be zero for grids where bedrock elevation is higher than the extrapolated groundwater level. The gain or loss in groundwater volume for a 1 year time period, for example 1997–1998, is the sum of the differences of the groundwater grid volumes of years 1998 and 1997. After calculating the volume for two consecutive years, Eq. 6 can be applied to calculate the saturated groundwater recharge that occurred between these two consecutive years.

4 Numerical Results and Discussion

The hydrological budget method, Eq. 6, was used to calculate groundwater recharge for the Hemet subbasin from 1997 to 2005. The average declines in groundwater levels for the consecutive years are shown in (Table 2). The specific yield point values for the average declined groundwater depths for the same two consecutive years were

Table 2 Groundwater drawdown and precipitation in the Hemet subbasin for 1997/1998 through 2004/2005

Period	Drawdown (cm)	Precipitation (cm)	Weather condition
1997–1998	15	56	Wet
1998–1999	81	28	Dry
1999–2000	66	20	Dry
2000–2001	69	23	Dry
2001–2002	78	12	Dry
2002–2003	51	33	Normal
2003–2004	56	21	Dry
2004–2005	06	68	Wet

Table 3 Estimated groundwater recharge (MCM) for the Hemet subbasin for 1997/1998 through 2004/2005

Period	Weather condition	Groundwater withdrawals	Groundwater storage changes	Groundwater recharge	Groundwater recharge (%)
		MCM	MCM	MCM	
1997–1998	Wet	15.6	−0.85	14.8	95
1998–1999	Dry	13.8	−3.58	10.2	74
1999–2000	Dry	18.2	−4.7	13.5	74
2000–2001	Dry	18.7	−5.1	13.6	73
2001–2002	Dry	18.6	−4.6	14	75
2002–2003	Normal	14.2	−4.8	9.4	66
2003–2004	Dry	14.4	−4.9	9.5	66
2004–2005	Wet	16.2	−1.2	15	93
Totals		129.7	−29.7	100	77
1997–2005			23%	77%	

generated using the WET program. If the groundwater level drop/rise was less than 30 cm per time period, a 30 cm depth of drop/rise was assumed.

Table 3 shows the groundwater withdrawal for eight 1 year time periods, each from May 1st to April 30th of the succeeding year. It also shows the calculated groundwater recharge. The main sources of groundwater recharge in the Hemet subbasin are precipitation including mountain front recharge; irrigation return water; subsurface inflow from the Lakeview and Perris South subbasins' subsurface, seepage from Diamond Valley Lake and the Upper Pressure subbasin across the Casa Loma Fault; and percolation from recycled water storage ponds. The long-term average precipitation in the Hemet subbasin is 33 cm. The periods 1997–1998 and 2004–2005 were considered to be wet periods, while the periods 1998–1999, 1999–2000, 2000–2001, 2001–2002, 2002–2003, and 2003–2004 were considered dry periods, (Table 3). Total groundwater extraction from the Hemet groundwater basin from 1997 to 2005 was 129.73 MCM; however, 23% of it was supplied from saturated groundwater storage and 77% was the result of groundwater recharge (Table 3). The groundwater levels in the Hemet subbasin have dropped more than 4.3 m since spring 1997 (Fig. 3).

Table 4 Estimated groundwater recharge components percentage for the Hemet subbasin for 1998 through 2005

Year	Weather condition	Calc. GW recharge MCM	Estimated groundwater recharge components percentage				Total rech.
			Subsurface (%)	Precipitation (%)	Recycled water (%)	Irrigation (%)	Percentage (%)
1998	Wet	14.8	23	48	10	15	96
1999	Dry	10.2	31	27	14	21	93
2000	Dry	13.5	49	14	11	16	90
2001	Dry	13.6	48	16	11	16	90
2002	Dry	14.0	59	8	11	15	92
2003	Normal	9.4	72	28	16	20	135
2004	Dry	9.5	79	17	16	19	131
2005	Wet	15.0	45	35	10	12	103

Table 5 Root-mean-square-error for range of increase percentages for the specific yield for groundwater changes between years 2003 and 2004

Percent or range	±10	±20	±50	±75
RMSE	0.021	0.084	0.524	1.178

The average contribution of groundwater recharge during wet and dry periods was 94% and 72% of the total groundwater withdrawal, respectively (Table 3). The average groundwater recharge for the 1999–2002 dry period was calculated to be 13.7 MCM, which is approximately 92% of the groundwater recharged during wet periods (Table 3). The increases in groundwater recharge during the 1999–2002 dry period were mainly the result of subsurface inflow (Table 4). The estimated percentage of the contribution of the groundwater recharge components are presented in Table 4. Groundwater levels of the Lakeview, Perris South, and Hemet subbasins were analyzed to estimate subsurface inflow during dry and wet periods. The results indicated that subsurface inflow represents about 50% of the total groundwater recharge during the 1999–2002 dry period, while less than 35% during the 1998 and 2005 wet periods (Table 4). Assuming 15% of precipitation percolates, the contribution of precipitation to groundwater during wet periods was more than 40%, while less than 20% of the precipitation contributed to groundwater recharge during dry periods (Table 4). The seepage from Diamond Valley Lake into the Hemet subbasin for high and low storage conditions is 4.92 and 3.32 MCM per year, respectively (Metropolitan Water District of Southern California 1991). The seepage from the lake can be considered as a continuous source of water for groundwater development in the Hemet subbasin. However, the subsurface inflows from adjacent basins should not be considered as a continuous sources of water because the amount of water in those basins can fluctuate. For example, development in the Lakeview and South Perris subbasins might include installation of new desalinization and municipal production wells thereby reducing groundwater in those subbasins. Also, groundwater recharge from precipitation may be reduced in the future due to urbanization.

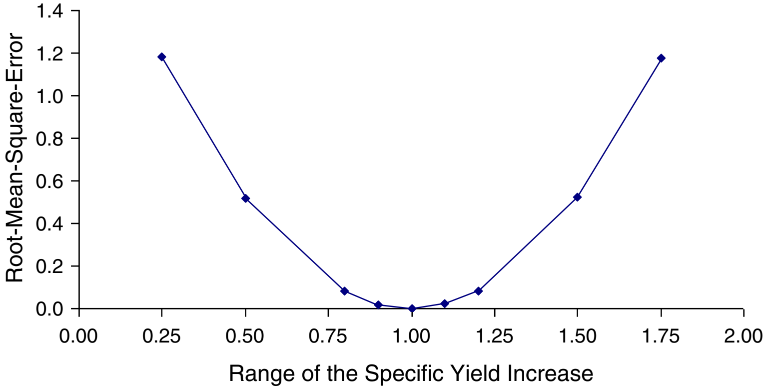


Fig. 5 Quantitative root-mean-square-error for range of multipliers

5 Summary and Conclusions

The proposed Hydrologic Budget Method requires information that is available to most groundwater management agencies, such as groundwater level measurements, groundwater extraction data, and well drillers' lithologic logs. The reliability of the method depends on the accuracy of these measured input components and estimated specific yield from lithologic descriptions. These data are readily available and/or obtainable. Groundwater levels can accurately be estimated using electric sounders. Groundwater extraction data is usually collected by the well owner and the State and is recorded accurately using meters on production wells. In addition, the proposed method captures variations in porous aquifer materials along aquifer depths and across the geographic basin. This methodology is sensitive to the specific yield values estimated by the WET program. For example, the results of the Root Mean Square Error (RMSE) in Table 5 indicate that the calculated changes in groundwater storage are sensitive to specific yield values that are greater/less than (±) 20% of the values estimated by the WET program. The estimated specific yield values for the average change in groundwater depths for the period between 2003 and 2004 were multiplied by a range of percentages (−75% to 75%) to measure the RMSE (Table 5) which is a measure of the accuracy of the predicated value to the measured value. Also, qualitative inspection of Fig. 5 shows that the changes in the slope of the curve for the −20% to +20% range of the multiplier is small, while the changes in the slope of the curve increase sharply when the ranges are greater than 20% or less than −20% of the specific yield.

This method was applied to the Hemet subbasin to estimate groundwater recharge for both dry and wet periods. Matched pairs of groundwater level measurements from the same wells were used for developing water surface grids for each year, and the WET program was used to create a spatial distribution for the specific yield data that was utilized for quantifying changes in saturated groundwater storage. The average contribution of groundwater recharge during wet and dry periods was found to be 94% and 72% of the total groundwater withdrawal, respectively. The analysis of the groundwater levels indicated that subsurface inflow represents approximately 50% of the total groundwater recharge during the 1999–2002 dry period, while it was less than 35% during the 1998 and 2005 wet periods. The contribution of precipitation to groundwater during wet periods was more than 40%, while less than 20% of the precipitation contributed to groundwater recharge during dry periods. Average contributions of recycled and irrigation water to groundwater were more than 10% and 15%, respectively.

The method described above is simple, cost-effective, and easy to apply and it produces reasonable and acceptable results. In addition, its application does not require sophisticated expertise and is, therefore, well suited to water agencies or other water management entities with limited resources.

Notation

The following symbols are used in this paper:

A_{gb}	Area of the geographic basin;
ET	Evapotranspiration;

IP	Intercepted precipitation by vegetation;
Q_{bf}	Groundwater discharge to streams (baseflow);
Q_{in}	Subsurface inflow;
Q_{out}	Subsurface outflow;
Q_{w}	Groundwater withdrawal through pumping wells;
R	Groundwater recharge;
RO	Surface water runoff;
SY	Average specific yield;
W	Applied water on ground surface;
ΔH	Average change of the measured groundwater levels per time period; and
$\Delta \mathrm{S}$	Change in saturated groundwater storage.

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