Estimation of Groundwater Recharge Using Water Balance Model Coupled with Base flow Separation in Bulbul River Catchment of Gilgel-Gibe River Basin, Ethiopia

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ABSTRACT

Sustainable development, use and management of groundwater resources is a challenge under the current population growth, land degradation, climate change and economic development require proper quantification of groundwater recharge. Therefore, this study anticipated the amount, spatial and temporal variability of groundwater recharge at the Bulbul River Catchment of Gilgel-Gibe River Basin (Ethiopia) using the soil mass balance method in conjunction with base-flow separation method. The result shows coefficient of groundwater recharge by the precipitation is estimated to be 23.07% and 25.62% from the established soil moisture budget model and the base-flow model respectively. Even though, change in groundwater storage in the area is positive, the river flow demonstrated a seasonal shift from summer to autumn. This change may substantially alter seasonal water retention capacity in the river catchment and irrigation development in the floodplain following the embankment. Hence, supplementary irrigation water application at the time of water shortage in the area is highly recommended.

Key words: Riverbasin, Groundwater, Recharge, Discharge, Water budget, Base flow.

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INTRODUCTION

The availability and access to freshwater resources are considered to be a determining factor for economic growth and social development patterns. Groundwater, which constitutes 97% of fresh water of the world, is potable at source, available in-situ and has a low temporal variability (Taylor and Barrett, 1999). These characteristics have made groundwater the most important source of water for the current generation. Globally, over two billion people depend directly upon groundwater for drinking water. Moreover, about 40% of the world’s irrigated agriculture depending largely on it (UNESCO, 2004).

Owing to increased demand and natural climate change, groundwater is often abstracted beyond its natural recharging capacity resulting in depletion of the resource (Badie et al., 2002). The amount of water potentially to be extracted from an aquifer without causing depletion is primarily dependent on the groundwater recharge. Thus, a quantitative evaluation of the resource is a pre-requisite especially in developing countries like Ethiopia, where most people rely on it as a source of potable water and domestic uses. In Ethiopia, more than 70% of domestic water supply depending on groundwater resource (EAH, 2007).

Bulbul River Catchment, located in Gilgel-Gibe River Basin of Ethiopia, is under pressure from population growth and climate change. Most of the previous researches are mainly focused on surface water, and little information is known about the groundwater potential of the area. There is an urgent need to investigate the groundwater hydrology of the area. The current study, therefore, presents the status of groundwater recharge in the Bulbul River Catchment of Gilgel-Gibe River Basin (Ethiopia). The study result is expected to contribute to the sustainable development and management of the groundwater resource in the region.

MATERIALS AND METHODS

STUDY AREA

Bulbul River Catchment is locating in the vicinity of Gilgel Gibe Sub- River basin of Omo-Gibe basin, which is one of eight main drainage basin of Ethiopia. It is locating (7°31’-7°58’N and 36°51’-37°9’E) at a distance of about 335Km South-west of Addis Ababa.
The area is bordering by the Jimma town in the North-East side. Bulbul River is one of the perennial tributaries of the Gilgel Gibe River draining an area of 507.85 km² carrying mean annual flow of over 235 million m³. Elevation of the area ranges between 1,800 and 2,800 mean above sea level. The mean annual temperature of the area is 20°C. In general, the study area is characterized by a wet climate with an average annual rainfall of about 1,520 mm, and 60% occur from June to September.

The soil texture of the area ranges from clay to that of sandy loam with a hydraulic conductivity in the ranges of from 33.56 to 148.82 cm/day. Figure 4 shows the distribution of different soil type in the study area. Geologically, the area comprises rocks that range from Precambrian to Quaternary, more dominantly Pliocene age volcanic with a thick succession of basalts and slick rocks which show a conformable relationship but they lie unconformable over the Precambrian basement (Mengesha et al., 1996). The area is dominated by Nitisols followed by fluvial soils.

**Data Collection**

Thirty years (1982-2011) meteorological data (rainfall, temperature (maximum and minimum), relative humidity, sunshine hours, and wind speed) of four meteorological stations, namely Jimma, Limmu-Genet, Asendabo and Sokoru were taken from the National Meteorological Agency of Ethiopia. Similarly, 20 years (1986-2005) daily gauged data of Bulbul and Gilgel Gibe Rivers obtained from the Ministry of Water, Irrigation and Energy of Ethiopia. Besides, land use and cropping pattern data of the study area were obtained from Keressa Wereda Agriculture and Development Office.

Moreover, indigenous irrigation water application depth, groundwater level inspection and draft from groundwater were carried out in selected fields. Missing values of historical climatic data were filled using appropriate methods. Normal ratio method (Equation 1) was used to fill missing values for precipitation. For other climatic variables, multiple regression methods (Equation 2, Xia et al., 1999) were used.

\[
V_o \frac{\sum_{i=1}^{n} W_i V_i}{\sum_{i=1}^{n} W_i}
\]  

(1)
\[ V_o = a_0 + \sum_{i=1}^{n} (a_i V_i) \]  

(2)

Where \( V_o \) is estimated missing value, \( W_i \) is weight of the \( i^{th} \) nearest weather station, \( V_i \) is the observational data of the \( i^{th} \) nearest weather station and \( a_0, a_1, \ldots, a_n \) are regression coefficients.

**Recharge Estimation**

Some of the groundwater recharge estimation methods commonly used include water balance, Darcy physical methods, chemical, and isotopic methods (Kinzelbach et al., 2002). Each of the methods has its own advantages and drawbacks in terms of applicability and reliability. Estimating the rate of aquifer replenishment is inevitably subject to errors and no single comprehensive estimation technique has been identified. Clarity on the aim of the groundwater recharge study is crucial in selecting appropriate methods for recharge estimation, which must be according to the data input available. In the current study water balance method was used to quantify groundwater recharge. Water balance model is still used in many studies from catchment scale to global scale (Lerner et al., 1990; Mintz and Walker, 1993). The advantage of the water balance method is that recharge can usually be estimated from readily available data (rainfall, runoff, water levels) and rapid to apply.

**Development of Water Balance Model**

Water balance of the Bulbul river catchment was presented schematically in Figure 3 which shows inflow and outflow from groundwater storage. It is a bookkeeping process between recharging and the discharging component (Equation 3). Estimating groundwater inflow and outflow is the most difficult to evaluate because they cannot be directly measured, often one of them, or the difference, is fixed by being the only unknown in the equation. Hence, the boundaries of the water budget are usually delineated deliberately to coincide with the water shed boundaries, and groundwater inflow and outflow are assumed equal (Fish, 2011). Other water balance components such as recharge from canal seepage, recharge from tanks, influent seepage from and effluent seepage to rivers were reasonably neglected as their effect may abandon each other.

![Figure 3. Diagram for water balance modified from W.H. Freeman and Company (2007)](image-url)
\[ I - O \pm \Delta S = 0 \] 3

Where I represents an input to the system, O is an output from the system and \( \Delta S \) is change in storage of the system. The basic steps followed in recharge estimation were: (i) formulating the general water balance equation, (ii) identification of significant components, and (iii) evaluating and quantifying individual components. Hence, looking at characteristics of geographic region and availability of data, water balance model of the study area was simplified as:

\[ R(t) = P(t) + RI(t) - ET(t) - q(t) - Q(t) - \Delta S(t) \] (4)

Where \( R(t) \) is groundwater recharge, \( P(t) \) is precipitation, \( RI(t) \) is recharge from an irrigated field, \( ET(t) \) is evapotranspiration, \( q(t) \) is a draft from well, \( Q(t) \) is rainfall excess (runoff), and \( \Delta S(t) \) is the change in groundwater storage in cubic meter on a yearly base.

All the components of water balance described in (Equation 4) were determined systematically. Potential \( ET \) for a reference crop (\( ET_o \)) was calculated by CROPWAT (Version 8.0) computer program using Penman-Monteth method. Whereas, Actual evapotranspiration (\( ET_c \)) was obtained by multiplying \( ET_o \) by crop coefficient (\( K_c \)) obtained from FAO working paper. Similarly, runoff for the river catchment was determined from river-gauged data at the outlet that quantifies over all discharges. In addition, change in soil moisture content was predicted by gravimetric method for the soil profile at depth of 20, 60, 100 and 150 cm for both dry and wet periods. Finally, Richards’s differential equation (Equation 5) was used to determine the change in soil moisture content in the river catchment.

\[ S = \frac{Q(Z_1) + Q(Z_2)}{2} \cdot \Delta Z \] (5)

Where \( Q \) is the water content (m\(^3\) m\(^{-3}\)) at specified depth, \( Z_1 \) & \( Z_2 \) are soil profile depth and \( \Delta Z \) describes the difference between the profiles.

Moreover, FAO recommendations for developing country (5-15 l/day/person) were used for quantum analysis of the draft from groundwater for household consumption. For this study, an average of 10 l/day/per was used after informal discussion with farmers. Likewise, four irrigation schemes located in the river catchment were selected of which three representative farmers taken to investigate their water application to quantify recharge due to applied irrigation. Partial flume was used to measure incoming flow and the bottom of the field dike to inhibit tail water measurement. The farmers were allowed to irrigate their land as usual recording time elapsed to complete irrigating the entire area. Finally, the farmers were interviewed for application interval and the average number of applications for all stages of the crop. Mass balance for the irrigated plot was used to obtain percent share of crop water requirement recharging groundwater from irrigated land. The mean value of percent share of crop water requirement, joining groundwater was used to quantify groundwater recharge due to irrigation in the river catchment.

**BASE FLOW ESTIMATION**

Determining quantum of groundwater recharge alone gives indistinct information about groundwater and leads to an incorrect decision. Accordingly, detailed study of hydrogeology of the aquifer surrounding the study area is conditioned from available data. Hence, the data were passed under different analysis like base flow separation and flow duration curve. Hydrograph of observed river flow data was developed purposefully.
for the time series of 1986-1995 and 1996-2005 and base flow separation was worked out using recursive digital filter method. Likewise, the flow duration curve of 20 years daily river gauged data in which the shape of low-flow conditions (exceeded 50% of the time) of the graph drawn that indicates the hydro-geological characteristics of the area.

**RESULT AND DISCUSSION**

**WATER BALANCE COMPONENTS**

Table 1 presents the monthly groundwater recharge from irrigated fields for the crops grown in the study area. Precipitation and return from an irrigated field are the only recharging component in the river catchment. Assessment made on indigenous irrigation application in the area reveals that about 24% of required irrigation water percolate deep into the ground and recharge groundwater. This result well agrees with Taji and Hanson (1990) finding. Hence, 24% of irrigation water needs were account for deep percolation to groundwater recharge. The deep percolation from irrigated meadow varies from zero in the month of October to 825 ha.m /dec in the month of December.

Table 1. Groundwater recharge from an irrigated field (m$^3$)

<table>
<thead>
<tr>
<th>Month</th>
<th>Maize</th>
<th>Potato</th>
<th>Tomato</th>
<th>Others</th>
<th>total</th>
<th>Deep percolation from an irrigated field</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oct</td>
<td>0.0</td>
<td>0.1</td>
<td>0.0</td>
<td>0.0</td>
<td>0.1</td>
<td>2.3</td>
</tr>
<tr>
<td>Nov</td>
<td>6.9</td>
<td>21.4</td>
<td>7.0</td>
<td>1.9</td>
<td>37.2</td>
<td>1343.3</td>
</tr>
<tr>
<td>Dec</td>
<td>25.9</td>
<td>26.8</td>
<td>25.8</td>
<td>16.8</td>
<td>95.3</td>
<td>3440.0</td>
</tr>
<tr>
<td>Jan</td>
<td>30.3</td>
<td>20.4</td>
<td>25.3</td>
<td>18.0</td>
<td>93.9</td>
<td>3391.7</td>
</tr>
<tr>
<td>Feb</td>
<td>28.0</td>
<td>1.9</td>
<td>5.4</td>
<td>7.8</td>
<td>40.0</td>
<td>1444.3</td>
</tr>
<tr>
<td>Mar</td>
<td>4.3</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>4.3</td>
<td>154.0</td>
</tr>
<tr>
<td>Total</td>
<td>95.3</td>
<td>70.6</td>
<td>63.5</td>
<td>44.4</td>
<td>270.7</td>
<td>9775.7</td>
</tr>
</tbody>
</table>

Table 2 presents estimated values of ET for different land use and land cover in the Bulbul River Catchment. It accounts in the area for over 153Mm$^3$ of water loss. Similarly; 275Mm$^3$ of water leaves the catchment in the form of rainfall excess yearly. According to CSA (2007) report, the population density is 302 person pre km$^2$, and there are about 153,370 people resides in the river catchment. Hence, the amount of water abstracted for domestic consumption (Considering average rate of 10 l/day/person) was found to be in the order of 560,184 m$^3$/year.

Table 2. Estimated value of Evapotranspiration

<table>
<thead>
<tr>
<th>CN</th>
<th>Parameter</th>
<th>Area (ha)</th>
<th>Estimated value of ET(m$^3$/ha/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>perennial crop</td>
<td>28557</td>
<td>98,233,022</td>
</tr>
<tr>
<td>2</td>
<td>free water surface</td>
<td>250</td>
<td>3,287,025</td>
</tr>
<tr>
<td>3</td>
<td>rain fed</td>
<td>25707</td>
<td>48,335,303</td>
</tr>
<tr>
<td>4</td>
<td>irrigated field</td>
<td>3611</td>
<td>3,473,286</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>58125</td>
<td>153,328,636</td>
</tr>
</tbody>
</table>
Table 4 presents summary of groundwater balance components for Bulbula sub-basin. In water balance analysis, precipitation and recharge from an irrigated field was the recharging components. Whereas runoff from the sub-basin, ET, water abstraction for domestic use and change in soil moisture content considered as the discharging component. Hence, with application of water balance model described above substituting the results for each component in the area groundwater recharge exceeds discharge by mean annual value of 178,067,792 m$^3$ which is corresponding to 23.07% of mean annual precipitation fall in the area.

<table>
<thead>
<tr>
<th>Date</th>
<th>depth</th>
<th>Reading sites (m$^3$/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Jan</td>
<td>20</td>
<td>27.96</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>35.94</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>46.54</td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>31.94</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>30.45</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>36.37</td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>46.54</td>
</tr>
<tr>
<td>S(t1)</td>
<td></td>
<td>0.14</td>
</tr>
<tr>
<td>S(t2)</td>
<td></td>
<td>0.08</td>
</tr>
<tr>
<td>∆S</td>
<td></td>
<td>0.06</td>
</tr>
</tbody>
</table>

| total soil moisture content change (m$^3$/m$^3$) | 0.0892 |
| change in soil moisture content (m$^3$) | 25,289,436.00 |

**BASE FLOW ESTIMATION**

Hydrograph was developed forrrier gauged data of 1986-1995 and 1996-2005 time series purposefully. The developed hydrograph was separated in to base flow and quick flow. Details of the Bulbul River flow hydrograph with its base flow separated were presented in Figures 4 and 5. As it is shown clearly in the graph, the river carries more or less constant discharge in winter and spring seasons. The mean river flow begins rising in the summer and attains its peak almost at the end of the season, and the flow resides in the autumn season for both periods. However, the graph is characterized by gentle rising limb and steep recession limb for the former time series, and it reversed for the later period. This change shows that existence of the seasonal change in river flow in the area that may be due to the seasonal budge in precipitation and or change in hydro-geological characteristics over time. Nevertheless, the mean annual river flow showed neither increasing nor decreasing trend under 95% confidence level of the Mann Kendal test. The overall contribution of ground water to surface water that believed equivalent to groundwater recharge estimated at 206,305,567 m$^3$ of water, and it accounts 26.7% of mean annual precipitation fall in the area.
For detailed understanding of hydrogeology of the study area frequency duration curve of the observed river gauge data was analyzed seasonally. As shown in Figure 6 that shows FDC of Bulbul River for each season. When we consider general character of low flow condition (exceeded 50% of the time) of the graph, the graph shows gently in winter followed by autumn. Whereas, during spring and summer the shape of the graph shows relatively steep. Hence, the contribution of base flow to stream is significantly large in winter and autumn relative to other seasons this is may be because 60% of rain falls during summer recharging to groundwater storage in the study area, and the effect prevails slowly during those seasons.

**CONCLUSIONS**

In view of increasing demand of water for various purposes sustainable utilization of the resource, requires proper quantification of groundwater. Hence, water balance competitions, coupled with base flow analysis were performed in the river catchment using long-term average climatic and physical data. The coefficients of groundwater recharge by precipitation in the study area predicted from established water budget...
analysis and base flow model were 23.07% and 25.62%, respectively. The result of both methods is quite close with the difference as small as 2.55%. Moreover, the groundwater level in the area illustrated both spatial and temporal variation in such a way that groundwater attain the maximum level in the month of September through October, and it decreases beyond these months continually and reach equilibrium in the month of February attaining the lower level.

REFERENCES


United Nations Educational, Scientific and Cultural Organization World Water Assessment