ESTIMATING GROUNDWATER RECHARGE INTO A SHALLOW UNCONFINED AQUIFER IN BANGLADESH

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ABSTRACT

This paper presents a data conservative approach, in which quantitative groundwater recharge estimation in a shallow unconfined aquifer is interpreted in detail by the analysis of observed precipitation and water level fluctuations records. Kushtia district in Bangladesh has been taken as a case study area based on the observed data and information. In the adopted state-of-the-art methodology used for this study, well-known water table fluctuation technique has been modified so that groundwater recharge in shallow aquifer can be estimated by using the least available data and information. Observed time series of precipitation and groundwater levels records at a few monitoring wells in the study area are the only data required to carry out the study. The approach illustrated in this paper can be useful in any initial level of assessment in groundwater studies. In addition, results can be applied as input data for developing numerical groundwater model for any groundwater resource investigation in the study area or similar drainage basins in Bangladesh.

Keywords: Groundwater recharge, Kushtia, Precipitation, Unconfined aquifer, Water table fluctuation

1. INTRODUCTION

Groundwater (GW) recharge is defined as the fraction of total precipitation falling into a drainage basin, which eventually reaches the water table in the saturation zone of an aquifer (Jukić and Jukić, 2004). It is a fundamental component of GW systems (Sanford, 2002), because information on GW recharge rates is often necessary for water resource management, inputs to regional GW models and predictions of climate change impacts (De Silva and Ruston, 2007). Thus, GW recharge is a critical hydrological parameter, which may need to be estimated at a variety of spatial and temporal scales depending on the application. Since GW recharge cannot be measured directly, it is often estimated by using the results of hydrogeologic and geologic investigations, hydro-meteorological data, observed discharges or GW level hydrographs (Jukić and Jukić, 2004). However, aquifer-scale recharge estimation is often required for water resource assessment and management, whereas local-scale recharge is critical to assessment of GW contamination from point sources. Estimation of GW recharge may be required on temporal scales ranging from days to thousands of years. As aquifers are depleted, recharge estimation have become more vital in determining appropriate levels of GW withdrawal. In addition, recharge estimation is becoming more important for contaminant transport, as aquifer management expands from cleanup of existing contamination to aquifer protection by delineation of areas of high recharge (Scanlon and Cook, 2002). Thus, understanding GW recharge and its accurate estimation is essential for the successful management of water resources and modelling fluid flow and transport of contaminants within the subsurface (Healy, 2010; Healy and Cook, 2002). Increasing demand for recharge estimation is forcing the researchers to develop approaches for building a more thorough understanding of aquifer recharging process and quantifying recharge rates that reduce uncertainties and increase confidence in recharge estimates (Scanlon and Cook, 2002).

The fraction of precipitation that reaches the phreatic zone in an aquifer depends upon several factors including soil, topography, vegetation, and climate (Moon et al., 2004). Because of such influencing factors, determining the GW recharge into aquifers is one of the great challenges in almost all the GW studies (Korkmaz, 1988). Depending on the available hydrological data and information, numerous techniques for estimating GW recharge have been discussed intensively in the literatures (Venetics, 1971; Rushton and Ward, 1979; Caro and Eagleson, 1981; Johansson, 1987; Das Gupta and Paudyal, 1988; Korkmaz, 1988; Bekesi and McConchie, 1999; Arnold et al., 2000; Edmunds et al., 2002; Flint et al., 2002; Lewis and Walker, 2002; Scanlon et al., 2002; Jukić and Jukić, 2004; Moon et al., 2004; Anuraga et al., 2006; Rahman and Roehrig, 2006; Ruston et al., 2006; Sharda et al., 2006; Thomas and Tellam, 2006; Batelaan and de Smedt, 2007; Coes et al., 2007; De Silva and Ruston, 2007; Park and Parker, 2008; Martínez et al., 2009; Niziku et al., 2009; Izuka et al., 2010; Jie et al, 2011; Singh, 2011; Yin et al., 2011). However, most of these approaches often require much time and skill along with lots of

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hydrological data and information, since they apply numerical modeling techniques for estimating GW recharge into aquifer. Very often, the necessary data and information are not readily available and the cost of using such models may sometimes be prohibitively very high (Das Gupta and Paudyal, 1988) for a developing country like Bangladesh. Therefore, simple and straightforward method should be developed for estimating GW recharge from a few input variables that are relatively easy to collect for most regions. Measurements of GW level fluctuations along with precipitation events establish a practical means of estimating temporally and spatially variable GW recharge rates, which have been illustrated by using a number of methods in several literatures (Veneetics, 1971; Rushton and Ward, 1979; Caro and Eagleson, 1981; Johansson, 1987; Das Gupta and Paudyal, 1988; Korkmaz, 1988; Sophocleous, 1991; Rai and Singh, 1995; Bierkens, 1998; Rai and Manglik, 1999; Knotters and Bierkens, 2000; Coulibaly et al., 2001; Healy and Cook, 2002; Rai et al., 2006). However, GW level fluctuation is not only worth of estimating recharge, but also it can provide a practical means of estimating other hydrological parameters as well (Bauer et al., 2004). In this respect, the water-table fluctuation method can be a good choice for estimating GW recharge in shallow aquifer, which requires only the knowledge of specific yield and changes in water levels over time. Advantages of this approach include its simplicity and insensitivity to the mechanism by which water moves through the unsaturated zone (Healy and Cook, 2002). This paper presents a data conservative modified water-table fluctuation approach, in which quantitative estimation of GW recharge in the shallow unconfined aquifer in Kushtia district of Bangladesh is interpreted by analyzing the precipitation and GW level data. It is expected that the methodology described in this paper can be applied as preliminary input parameters for developing and simulating a GW model in the numerical environment for any GW resource investigation scheme in the study area or similar catchments in Bangladesh.

2. METHODOLOGY

2.2 System Conceptualization and Mathematical Formulation

Records of GW level fluctuations in monitoring wells are worth the cost and trouble of collecting only if they are used as a basis for hydrologic interpretations and for subsequent applications in hydrological investigations. Although water level records have been important to draw conclusions regarding the occurrence and development of GW in specific areas under concern, many such records still await interpretations. Similarly, a wealth of climatologic and other hydrologic data is in need of analysis before taking the final conclusions (Korkmaz, 1988). In the wet period of a water year, when the precipitation occurs, the first rain wets vegetation and accordingly other surfaces and then begins to infiltrate into the ground depending on the surface characteristics.

Figure 1a GW level fluctuations in arithmetic scale caused by the recharge from precipitation
In general, it is possible to calculate the total level oscillation amplitude due to infiltration of the precipitated water, if the overall recession regime (i.e. the behavior of the aquifer without external recharge) is known (Korkmaz, 1988). It is generally found that the component forming a GW hydrograph having a recession can be approximated by a simple exponential relationship (Subramanya, 1994) of the form (Figure 1) as expressed in Equation (1).

\[ h = h_0 e^{-\alpha t} \]  

(1)

Where, \( h_0 \) and \( h \) are the water level above discharge level at the beginning of the measurement period and at any certain time \( t \), respectively and \( \alpha \) is known as coefficient of recession or discharge coefficient.

Like any other exponential formula, on a semi-logarithmic paper when water level above discharge level is plotted to the log scale and time to the arithmetic scale, the recession curves plot as nearly as straight lines (Figure 1b). In the logarithmic system with base 10, the formula is converted into the linear form as described in Equation (2)

\[ \log h = \log h_0 - 0.43429 \alpha t \]  

(2)

The shape of the recession curve depends on the water yielding properties of the aquifer material, the transmissivity and the aquifer geometry (Johansson, 1987).

The recovery of the water level, \( \Delta H \) under natural hydrological conditions is a mirror image of the recession curve obtained from GW level fluctuations. The recovery of the water level varies from year to year, depending on the amount of total precipitation \( (R_t) \) in wet period of a water year (Figure 1a). However, GW levels are influenced by the seasonal cycles (Almedeij and Al-Ruwaih, 2006; Adhikary et al., 2012), which are relevant to different factors such as recharge from precipitation, evapotranspiration, overland flow and runoff, and discharge from wells and shows a seasonal pattern of fluctuations (Healy, 2010). The degree of correlation between fluctuations of GW level and variations in total precipitation \( (R_t) \) in wet period of a water year provides an evidence as to the freeness of the connection between the aquifer recharge and total precipitation \( (R_t) \) in wet period of a water year (Korkmaz, 1988). In this study, the direct estimation of GW recharge in shallow aquifer is considered using recovery of the GW level \( (\Delta H) \) and total precipitation \( (R_t) \) during wet period in a water year.
The linear regression model developed by the relationship between $\Delta H$ and $R_t$ can be expressed by Equation (3).

$$\Delta H = a + bR_t$$

Where, $\Delta H$ is recovery of GW level, and $R_t$ is total precipitation during the wet period in the water year under consideration, $a$ and $b$ are the regression coefficients of the linear regression model expressed by Equation (3). This process is diagrammatically presented in Figure 2.

Figure 2 Relationship of total precipitation in wet period and recovery of the aquifer water level

Figure 2 indicates that the precipitation intercept, $Re$ is the intersection of the total precipitation recovery straight line with zero-total precipitation axis. It represents the amount of surface runoff and evapotranspiration for the same period. Recovery or recharge from rainfall is a function of the amount of total precipitation ($R_t$). If the intercept is $Re$, the recharge ($Rs$) can be estimated by the Equation (4), which is expressed as

$$R_s = R_{tc} - R_e$$

Where, $R_{tc}$ is the computed total precipitation by means of Equation (3) during the wet period in a water year. However, the major features of this proposed methodology is that it indirectly estimates the water losses such as evapotranspiration and surface runoff. It can be found by subtracting the recharge amount from the total precipitation quantity.

2.2 Estimation of Groundwater Recharge

In this paper, a modified data conservative GW fluctuation technique is presented for estimating GW recharge in a shallow unconfined aquifer of Bangladesh based on the statistical relationship between the precipitation and water levels. The analysis is based on the original conditions, which are unaffected by heavy pumping. Observed monthly precipitation records and weekly GW levels are the only data required to carry out the study. Data have been collected from the central database of Bangladesh Water Development Board (BWDB). For this study, daily rainfall data at a precipitation data collection station (BWDB rainfall station ID: CL41) and GW level fluctuation data at a monitoring well (BWDB GW level monitoring station ID: GT5015004) are collected for the 16 years period from 1992 to 2007. However, these two representative monitoring stations located in the study area have been selected depending on the data availability for a longer period. Shallow aquifer located in the upper part of the Gorai River catchment (mainly Kushthia district area) in Bangladesh has been selected as a case study area (Figure 3). The upper part of aquifer in this region is unconfined in nature (Halcrow, 1993; Adhikary,
2009) and GW is extensively extracted from its shallow depth due to the increased irrigation activities (Halcrow, 1993; Adhikary et al., 2011; Adhikary et al., 2012).

By analyzing the monthly precipitation data and water level records belonging to the 16 years period from 1992 to 2007, the amount of rainfall causing a rise in water level is determined. These rainfall amounts are called “total precipitation \( R_t \)” causing the rise in water level. The water level rise caused by this total precipitation is termed as “water level rise due to GW recharge \( \Delta H \)” and can be found from the plotted graph directly. This procedure is repeated year after year for the period of total records of 16 years from 1992 to 2007 and the relationship between these two variables \( R_t \) and \( \Delta H \) is established by using simple statistical technique. However, \( \Delta H \) is a function of the precipitation amount above a threshold precipitation value, which represents the precipitation causing surface runoff, evapotranspiration, and subsurface flow or only one of them depending on the local hydrogeological conditions in the study area (Korkmaz, 1988). These values of water losses can be obtained by setting \( \Delta H = 0 \) in the regression equation, which has been schematically presented in Figure 2. The recharge amount for each water year is then calculated by subtracting the threshold precipitation from the total precipitation causing GW level rise in that particular year.

3. RESULTS AND DISCUSSION

Shallow aquifer located in the upper part of the Gorai River catchment (mainly Kushtia district area) in Bangladesh has been selected as a case study area (Figure 3) for this study based on the data availability from secondary source (i.e. Bangladesh Water Development Board). It covers an area of 1621 square kilometres and is bounded by Rajshahi, Natore and Pabna districts to the North, Chuadanga and Jhenaidah districts to the South, Rajbari district to the east and West Bengal and Meherpur district to the west. The upazillas (sub-district) are Kushtia Sadar, Kumarkhali, Daulatpur, Mirpur, Bheramara and Khoksa. The Ganges, the Gorai, Mathabhanga, Kaligonga and Kumar are the main rivers flowing through the district. The average maximum and minimum
temperatures are 37.8°C and 11.2°C, respectively with an average annual rainfall of 1,898 mm. The GW levels naturally fluctuate in response to a sequence of climatic events and to constraints imposed by the hydrogeologic and topographic characteristics, which is presented in Figure 4.

Figure 4 reveals that the aquifer is recharged in the wet period of a water year (April to next March in a year) in Bangladesh (Mirza, 1997) due to the heavy rainfall in that time and discharged out of it in the dry period as there is not much rainfall available in that time. In addition, evapotranspiration and water withdrawal takes place in various ways by numerous human interventions, which cause the depletion of the GW level. However, GW recharge is the largest in the wet period of a water year, especially in the monsoon season, when plants are dormant and evapotranspiration rates are comparatively less. Besides, in the dry period of a water year, when evapotranspiration rates along with the GW extraction from underground shallow aquifer exceed the available moisture from precipitation, GW recharge to the water table is negligible in the shallow unconfined aquifer and consequently, GW levels decline.
The recovery of the water level ($\Delta H$) and the total precipitation ($R_t$) during the wet period in each water year for 16 years period from 1992 to 2007 are determined, which are presented in Figure 5. A linear regression model during the whole 16 years period is established and is schematically presented in Figure 6. The results of linear regression analysis are presented in Table 1. The regression equation is found as represented in Equation (5).

$$\Delta H = -1.06585 + 0.00521 \times R_t$$

The average precipitation intercept ($Re$) of the case study aquifer is found as 204.58 mm (Figure 6), which represents the amount of surface runoff and evapotranspiration for the same period. This result demonstrates that...
the proposed methodology described in this paper indirectly estimates the water losses such as evapotranspiration and surface runoff. It can be found by subtracting the recharge amount from the total precipitation amount. The obtained result is often useful in any initial level of assessment, where model input is primarily necessary while conducting detailed study using the numerical GW modeling technique.

\[
\Delta H = -1.06585 + 0.00521 \times R_t
\]

**Figure 6** Relationship of total precipitation in wet period and groundwater recovery

**Table 1** Results of linear regression analysis

<table>
<thead>
<tr>
<th>Type of relation</th>
<th>No. of observations</th>
<th>Correlation coefficient (r)</th>
<th>Standard error of estimate</th>
<th>Regression Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total precipitation-GW level recovery</td>
<td>16</td>
<td>0.84</td>
<td>1.49</td>
<td>(\Delta H = -1.06585 + 0.00521 \times R_t)</td>
</tr>
</tbody>
</table>

However, the computed values \((R_{tc})\) of total precipitation by means of the developed regression model for water years from 1992 to 2007 are summarized in Table 2. The results of the recharge \((R_s)\) computation based on the available precipitation for the total 16 years period from 1992 to 2007 by using the Equation (4) are presented in Figure 7. The annual GW recharge in the studied aquifer for the period ranges from 1794 mm in 1999 to 1140 mm in 2003 (Figure 7). The annual average recharge during the 16 years period is estimated as 1413 mm. However, this is about 74 percent of the average annual precipitation (1898 mm) occurs in the study area.

Estimated GW recharge by using the methodology proposed in this study is finally compared with the previous studies conducted in the present study area under the studied aquifer (Halcrow, 1993; Adhikary, 2009), which is presented in Figure 8. However, Healy (2010) describes that since actual recharge rates are unknown, so there are no standards by which the accuracy of estimated recharge can be evaluated. Figure 8 shows that the estimated GW recharge values for the whole 16 years period in this study are reasonably closer to those estimated by the two previous studies (e.g. Halcrow, 1993; Adhikary, 2009). Hence, the obtained result is regarded as quite reasonable for further applications. The estimated GW recharge based on three different studies presented in Figure 7 indicates that the modified GW fluctuation approach proposed in this study overestimates in some years as well as underestimates in other time periods with respect to the study conducted by Halcrow (1993) and Adhikary (2009). This proves the acceptability of the methodology proposed in this study in estimating GW recharge in an unconfined aquifer having shallow depth. However, it is noteworthy that these two previous studies applied the long-term water balance approach and numerical GW modeling technique, respectively for estimating the GW recharge in the studied aquifer. It is now widely recognized that both methods usually provide almost accurate results as they take into account lots of hydrological parameters (Moon et al., 2004), which actually influence the recharging process of the aquifer.
Table 2 Summary of GW recharge computation for the studied aquifer

<table>
<thead>
<tr>
<th>Water Year</th>
<th>Annual Precipitation, $R_y$ (mm)</th>
<th>Recovery of GW level, $\Delta H$ (m)</th>
<th>Computed Total Precipitation, $R_{tc}$ (mm)</th>
<th>Recharge, $R_s$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1992</td>
<td>1633.60</td>
<td>6.01</td>
<td>1356.21</td>
<td>1151.63</td>
</tr>
<tr>
<td>1993</td>
<td>2301.20</td>
<td>8.90</td>
<td>1912.83</td>
<td>1708.25</td>
</tr>
<tr>
<td>1994</td>
<td>1450.60</td>
<td>6.45</td>
<td>1442.58</td>
<td>1238.00</td>
</tr>
<tr>
<td>1995</td>
<td>1782.50</td>
<td>6.82</td>
<td>1513.60</td>
<td>1309.02</td>
</tr>
<tr>
<td>1996</td>
<td>1719.70</td>
<td>6.93</td>
<td>1534.71</td>
<td>1330.13</td>
</tr>
<tr>
<td>1997</td>
<td>2190.50</td>
<td>8.45</td>
<td>1826.46</td>
<td>1621.88</td>
</tr>
<tr>
<td>1998</td>
<td>2250.60</td>
<td>8.98</td>
<td>1928.19</td>
<td>1723.61</td>
</tr>
<tr>
<td>1999</td>
<td>2267.60</td>
<td>9.35</td>
<td>1999.20</td>
<td>1794.62</td>
</tr>
<tr>
<td>2000</td>
<td>1919.10</td>
<td>8.64</td>
<td>1862.93</td>
<td>1658.35</td>
</tr>
<tr>
<td>2001</td>
<td>1720.80</td>
<td>6.80</td>
<td>1509.76</td>
<td>1305.18</td>
</tr>
<tr>
<td>2002</td>
<td>1868.70</td>
<td>6.53</td>
<td>1457.94</td>
<td>1253.36</td>
</tr>
<tr>
<td>2003</td>
<td>1897.60</td>
<td>5.94</td>
<td>1344.69</td>
<td>1140.11</td>
</tr>
<tr>
<td>2004</td>
<td>1861.80</td>
<td>6.51</td>
<td>1454.10</td>
<td>1249.52</td>
</tr>
<tr>
<td>2005</td>
<td>1996.50</td>
<td>8.40</td>
<td>1816.86</td>
<td>1612.28</td>
</tr>
<tr>
<td>2006</td>
<td>1664.00</td>
<td>6.27</td>
<td>1408.03</td>
<td>1203.45</td>
</tr>
<tr>
<td>2007</td>
<td>1841.80</td>
<td>6.81</td>
<td>1511.68</td>
<td>1307.10</td>
</tr>
</tbody>
</table>

Figure 7 Estimated GW recharge for 16 years (1992-2007) in the study area
4. CONCLUSIONS

This study presents a modified water table fluctuation technique for estimating GW recharge by using only the precipitation and water level information for a shallow unconfined aquifer in Bangladesh. The overall goal of this study has been a synthesis of the results obtained by analyzing the GW level fluctuations and precipitation records. By following this principle, the study establishes a data conservative approach of estimating GW recharge in any shallow unconfined aquifer under concern. However, the accuracy of the results totally depends on the base of water level monitoring data. This study reveals that the shallow GW in the study area is recharged mainly from the precipitation sources. Besides, the annual average GW recharge in the studied aquifer is found as 1413 mm for total 16 years period from 1992 to 2007, which is about 74 percent of the average annual precipitation. However, the study concludes that the proposed data conservative methodology presented in this study provides appropriate mechanisms for indirect estimation of the water losses such as evapotranspiration and surface runoff, which will make this method useful in future hydrological computation for GW resource assessment and management in the field of water resources engineering. Finally, the present study conclusively proves that the proposed methodology described in this study will open a window of opportunity for any sorts of initial level assessment of GW resources in a shallow unconfined aquifer in Bangladesh, where shortest possible data and information are available.

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REFERENCES

International Conference of European Asian Civil Engineering Forum (EACEF 2011), Yogyakarta, Indonesia, 20-22 September, 2011. Available at:


