Combining Water Level Fluctuation Technique with Watershed Hydrologic Model for Daily Groundwater Recharge Estimation

N. W. Kim¹, Y. J. Kim¹ and I.-M. Chung¹
¹ Hydroscience and Engineering Dept., Korea Institute of Civil Engineering and Building Technology, 283 Goyangdae-ro, Goyang-si, Gyeonggi, 411-712, Rep. of Korea

1. INTRODUCTION

Groundwater level is a basic data that instructs changes of groundwater systems. It is the value that shows the physical state of groundwater and changes according to inflow, recharge and outflow, as well as the characteristics of the aquifer. Therefore, it can be viewed that the rise and drop of groundwater level represents the recharge and outflow of groundwater. Groundwater recharge is a process of the hydrologic cycle and as a process for precipitation permeating into the soil to pass soil deposits and unsaturated zones into the aquifer, it receives hydrogeological effects of the climate (precipitation, temperature, humidity, wind speed, etc), soil and soil use features, topography and subsurface geology. Therefore, even if it is the same region, it has various values regionally, and thus, the time-space variability must be taken into consideration to calculate the groundwater recharge (Memon, 1995).

The method for analyzing discharge using groundwater level fluctuation data has different names such as groundwater level fluctuation method, groundwater level descent method, aggregate groundwater level descent method, etc depending on the applied concepts and methods. These methods calculate the recharge rate for specific rise or descent sections to apply them in all sections, and therefore, it has the limitation of possibility of excessive estimation of recharge and that it cannot calculate recharge in short periods. In the groundwater fluctuation method, the specific yield of the aquifer is multiplied for the change of groundwater levels that occur during precipitation to calculate the groundwater recharge, and it is the most basic method applied in Korea and abroad since the 1920s (Healy and Cook, 2002). However, due to the limitations in the accuracy of the specific yield, there are difficulties in practical application (Kim et al., 2010).

For the proper management of groundwater, the natural groundwater recharge rate has to be identified. Since the accurate estimation of daily based recharge is difficult, seasonal or monthly based recharge rate is used for groundwater management. However, the impact of groundwater development affects the storage of aquifer directly, the time step of groundwater modelling to identify groundwater environment should be shorter than a month. In this work, a robust technique combining the transient water table fluctuation model (TWTFN) with a watershed hydrologic model, SWAT (Soil and Water Assessment Tool, Arnold et al., 2005) is suggested to estimate daily groundwater recharge.

2. GROUNDWATER FLUCTUATION ANALYSIS MODEL

De Zeeuw and Hellinga (1958) proposed a groundwater level variable formula integrating the groundwater discharge and drainage formula of Hooghoudt (1940). As shown in Fig. 1(c), due to the recharge brought in from the upper part, the ascended groundwater level begins to descend as the groundwater is discharged through wells or drainages in the aquifer. Therefore, groundwater level fluctuation occurs due to changes in the aquifer characteristics and storage amount due to the recharge and discharge of groundwater. Hooghoudt (1940) explained the head loss of groundwater in the storage state using the concept that when groundwater is recharged, it moves to the main flow direction of groundwater and in wells or drainages, it forms radial flow for discharge. The recharge of groundwater changes in space-time in relation to the climate conditions and soil, aquifer characteristics, topography and vegetation distribution, and land usage (Memon, 1995). Accordingly, recharge occurs through the mechanism that moves the soil deposits and unsaturated zones, and due to the characteristics of the unsaturated zone, the quantity and form of recharge changes in terms of time and space. When modeling the hydrological cycle process including the groundwater of saturation zones, it is as shown in Fig. 1, and (A) shows the soil deposits, (B) shows the unsaturated zones below the soil deposits, and (C) shows part of the saturation zone. Typically, (A) and (B) are called unsaturated zones in terms of the groundwater flow. However, in the actual hydrological cycle system, it is classified exactly.

Fig. 1 (A) shows the process of surface water forming if the precipitation is higher than the permeation rate into soil deposits and the process of permeating into the soil deposits if it is smaller than the permeation rate like the presumption of Horton (1940). Part of this permeation rate is discharged into the slopes of the soil deposit,
while the rest percolates into the lower soil deposit. Evapotranspiration also becomes active here. Final percolation into the soil deposit is reached after passing (B) shown in Figure 1, which is the pure unsaturated zone, and completes time delay and spatial expansion and finally comes to groundwater table (C) shown in Fig. 1, and this is called recharge. Due to the recharge time-series with time-space variability, the storage amount of the aquifer changes, which causes a rise or descent in groundwater level. Therefore, by analyzing the groundwater data, it is possible to identify the aquifer recharge or discharge features, and based on this, the groundwater recharge can be investigated.

![Diagram of groundwater table fluctuation](image)

**Figure 1 Conceptualization of groundwater table fluctuation (Kim et al, 2013)**

De Zeeuw and Hellinga (1958) proposed the transient water table fluctuation model (TWTFM), assuming that the recharge \( R_\Delta t \) is consistent during unit time \( \Delta t \), which is expressed in Eq. (1).

\[
h_i = h_{i-1} \exp[-\alpha \Delta t] + \frac{R_{\Delta t}(1 - \exp[-\alpha \Delta t])}{800 \mu \alpha}
\]  

(1)

Here, \( h_i \) is the groundwater level (L) in \( i \) days, \( h_{i-1} \) is the groundwater level (L) in \( i-1 \) days, \( \Delta t \) is the unit time (T), \( R_{\Delta t} \) is the aquifer recharge (L) in the unit time, \( \alpha \) is the reaction factor, and \( \mu \) is the specific yield, respectively.

Equation (1) can be modified to calculate the recharge, and when reorganised to solve for the recharge during unit time, \( R_{\Delta t} \), it is expressed as Eq. (2).

\[
R_{\Delta t} = \frac{(h_i - h_{i-1}) \exp[-\alpha \Delta t] \times 800 \mu \alpha}{1 - \exp[-\alpha \Delta t]}
\]  

(2)

In this study, this relationship is used as the basis of the model to calculate recharge per unit time.

There are two parameters in the transient flow groundwater fluctuation analysis method. One is the reaction factor \( (\alpha) \), which describes groundwater recession. When assuming no recharge, the groundwater level will decrease with groundwater discharge, and the reaction factor can be calculated using the decreasing curve. Specifically, Eq. (1) can be simplified as Eq. (3). Then, we can solve for reaction factor \( (\alpha) \) with the water level data during falling stage.

\[
h_i = h_{i-1} \exp[-\alpha \Delta t]
\]  

(3)

\[
\alpha = \ln\left(\frac{h_{i-1}}{h_i}\right)/\Delta t
\]  

(4)

The second parameter of the model is the specific yield (\( \mu \)). Rearranging Eq. (1) for the specific yield results in the expression shown in Eq. (4).
However, because the reaction factor and the recharge must be known in advance, the specific yield cannot be calculated directly. In this study, to determine $R_t$, the Soil and Water Assessment Tool (SWAT) is used to obtain groundwater recharge data for a specified period. These recharge data are then used to estimate the parameters in TWTFM.

3. WATERSHED HYDROLOGIC MODEL

The SWAT model was developed as a continuous long-term watershed model capable of simulating the movement of water, sediment, and pollutants using watershed status data, including soil, land use, pollution sources, etc., on a daily basis (Arnold and Forher, 2005).

In SWAT, soil water is determined by carrying out a water balance in three soil profile zones, soil water zone to plant root depth, unsaturated zone (vadose zone), and saturated zone (Eq. 6):

$$\sum = -\omega - Q_{sw} + E_a + Q_{gw}$$

where $SW_t$ represents soil water content at time (t), $SW_0$ is initial soil water content, $R_{day}$ is daily precipitation, $Q_{surf}$ is surface runoff, $E_a$ is evapotranspiration, $\omega_{seep}$ is deep percolation, and $Q_{gw}$ is stream return flow. The unit for all terms in Eq. (6) is mm.

The watershed of interest is divided into several sub-watersheds with similar hydrologic runoff characteristics. Each sub-watershed is then further divided into hydrologic response units (HRUs) commonly using the GIS technique by superposing the watershed soil map over the land use and extracting areas with similar soil and land-use types. All hydrologic components including surface, subsurface, and groundwater flow for each HRU are estimated and summed over the sub-watershed level. The land use of the watershed consists of deciduous forest (26.4%), the largest portion of the watershed, followed by evergreen forest (18.2%), agricultural crop (14.7%), and residential areas. There are 43 soil types in the watershed. Using this information, HRUs in SWAT are made for hydrologic component analysis.

4. APPLICATION

In order to apply the analysis model, the Hancheon River basin area of Jeju-do was selected, and the groundwater level data at JD Yongdam 1 and JW Konghang points that are operated by the Jeju Special Self-Governing Province's Water Resource Office (www.jejuwater.go.kr) are used (Fig. 2). Because the transient water table fluctuation analysis model (TWTFM) calculates recharge using the groundwater level data, dependency on actual measurements is very high. Therefore, the alluvial layer that shows the level change well was selected as the observation point (Kim et al., 2013). The Hancheon River basin located in the central north coastline of Jeju-do is made up of basalt such as trachy basalt and trachy, and the clicker layer that is developed in basalt acts as a pivotal role for groundwater recharge and flow. Fig. 3 shows the actually measured groundwater level and rainfall data at JD Yongdam 1 and JW Konghang. Rainfall data is collected from the Jeju Rainfall Observation Station and it is the observation data for five years (2006-2010) for each point. Upon observing the relationship of groundwater level and rainfall data, it was found that level ascent reaction was fast for both points. Furthermore, the groundwater level descent and ascent sections were shown clearly, making it easy to apply in the model. In the groundwater level data of 2007, rainfall rapidly increased creating a very rapid slope in the form of a spire for the groundwater level ascension part in a short period. This is judged to be the result of excessive measurement by having the rainfall directly being flown in to the observation well together with the ascent of groundwater caused by heavy rainfall in a short period of time. The two observation points, which are in geographic proximity, show overall similar forms in rainfall and groundwater level fluctuation.
Figure 2 Hancheon watershed and hydrologic monitoring stations (Kim et al, 2013)

Figure 3 Hancheon watershed and hydrologic monitoring stations (Kim et al, 2013)
The groundwater fluctuation analysis model was applied to calculate the recharge per unit time at JD Yongdam 1 and JW Konghang. The daily recharge of the calculated groundwater was used to examine the recharge form and characteristics of the examined points. The actual applicability of this analysis model was analyzed and the recharge was calculated using the calculated parameters. The parameters of the groundwater fluctuation analysis model used for the recharge analysis of JD Yongdam 1 and JW Konghang are as shown in Table 1.

<table>
<thead>
<tr>
<th>location</th>
<th>reaction factor(α)</th>
<th>specific yield(μ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>JD Yongdam1</td>
<td>0.039</td>
<td>0.023</td>
</tr>
<tr>
<td>JW Konghang</td>
<td>0.028</td>
<td>0.009</td>
</tr>
</tbody>
</table>

![Figure 4 Observed groundwater level and simulated recharge at JD Yongdam1](image1)

![Figure 5 Observed groundwater level and simulated recharge at JW Konghang](image2)
Figs. 4–5 are illustrations of the daily rainfall and estimated recharge during the applied period of the two points. It is evident that while recharge increases with rainfall, recharge also occurs when there is no rainfall. This occurs due to the mechanism where recharge moves the soil deposit and unsaturated zone as explained before, and it proves that the quantity and form is determined by the characteristics of the medium. When examining the recharge type of these two points, the overall discharge change is similar, but as shown in the groundwater observations of Fig. 3, it shows that because the two points have similar groundwater fluctuation form, the recharge process is also similar. However, there is some difference in short-term recharge form for event rainfall as shown in Figs. 4–5, and this is because the permeated amount has different recharge and discharge form according to the course of moving through the soil deposit. In other words, even if it is a nearby region, this occurs because the parameters change depending on the hydro-geological characteristics of the aquifer.

5. CONCLUSION

In order to calculate the groundwater recharge that fluctuates according to time and space, this study aimed at calculating the groundwater recharge by unit time in a regional scale with combining SWAT model. The groundwater level fluctuation formula proposed by De Zeeuw and Hellinga (1958) was modified into the groundwater fluctuation analysis model to calculate the recharge. In order to apply the analysis model, the groundwater level observation data (2006-2010) of JW Konghang and JD Yongdam 1 from the groundwater observation networks of the Jeju-do Hancheon region that has relatively good reaction to precipitation were used. For the applied parameters, the reaction factor of JD Yongdam 1 was 0.039 and its specific yield was 0.023, while JW Konghang was 0.028, 0.009, respectively. With combining SWAT’s annual recharge, the daily based groundwater recharge can be obtained. The overall fluctuation of the two points was similar, but there was a slight difference in the ratio between recharge and rainfall. The developed groundwater fluctuation analysis model is a method to calculate the parameters and recharge per unit time using the groundwater level data. Upon its actual application, it was found to be possible to well explain the characteristics of groundwater recharge, and thus is it judged that it can be used as a method to calculate groundwater recharge.

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