Development of an Apparent Recharge Coefficient (ARC) for Estimating Groundwater Storage Changes Due to Precipitation Events Using Time Series Monitoring Data

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Abstract: Significant variation in the precipitation events caused by global climate change has made it difficult to manage water resources due to the increased frequency of unexpected droughts and floods. Under these conditions, groundwater is needed to ensure a sustainable water supply; thus, estimates of precipitation recharge are essential. In this study, we derived an apparent recharge coefficient (ARC) from a modified water table fluctuation equation to predict groundwater storage changes due to precipitation events. The ARC is calculated as the ratio of the recharge rate over the specific yield (R/Sy); therefore, it implicitly expresses variation in $S_y$. The ARC varies spatially and temporally, corresponding to the precipitation events and hydrogeological characteristics of unsaturated materials. ARCs for five monitoring wells from two basins in Korea in different seasons were calculated using a 10-year groundwater level and weather dataset for 2005–2014. Then, the reliability of the ARCs was tested by the comparison of the predicted groundwater level changes for 2015 and 2016 with observed data. The root mean square error ranged from 0.03 to 0.09 m, indicating that the predictions were acceptable, except for one well, which had thick clay layers atop the soil layer; the low permeability of the clay slowed the precipitation recharge, interfering with groundwater level responses. We performed a back-calculation of $R$ from the $S_y$ values of the study areas; the results were similar to those obtained via other methods, confirming the practical applicability of the ARC. In conclusion, the ARC is a viable method for predicting groundwater storage changes for regions where long-term monitoring data are available, and subsequently will facilitate advanced decision making for allocating and developing water resources for residents, industry, and groundwater-dependent ecosystems.

Keywords: groundwater recharge; cumulative precipitation; time-series monitoring; water resources management

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) has reported variability in precipitation trends in Asia due to global climate change [1]. Specifically, the frequency and intensity of extreme weather events such as drought and flooding are expected to increase, leading to changes in the available water resources and increasing the vulnerability of groundwater resources [2,3]. To improve the sustainability of groundwater resources, the accurate estimation of groundwater recharge in response to the impacts of climate change is required for effective water management [4].

In the hydrologic cycle, groundwater is mostly recharged through the percolation of precipitation through the vadose zone and is discharged into surface water bodies slowly but steadily
through baseflow. When the water table is lower than the surface water, then groundwater is also recharged from the surface water resulting in losing streams. Thus, the distribution of groundwater recharge is highly variable in space and in time. In New Zealand, baseflow to streamflow, originating from groundwater and delayed by processes such as interflow, was reported to vary from 20 to 96%, with a mean of 53% [5]. The time scale of recharge varies depending on the characteristics of the precipitation events (e.g., amount, duration, and frequency) and the geologic materials within the unsaturated zone. For example, surface water bodies typically reflect the influence of precipitation within hours to days. However, groundwater may take from hours to decades to exhibit the influence of precipitation events, depending on site-specific hydrogeological characteristics. This extended response of groundwater systems to precipitation is the principal mechanism that sustains water supply for human societies, even during dry periods. For this reason, it is important to understand and monitor groundwater recharge processes [6–9].

Groundwater recharge is generally described as the vertical (downward) movement of water as it reaches the water table, adding to the groundwater reservoir and resulting in groundwater level rise [10]. Although precipitation is the ultimate source of water added to an aquifer, several factors affect the recharge process, including natural factors such as topography, soil hydraulic properties, aquifer materials, and vegetation, as well as human factors such as agricultural activity including irrigation [11]. These factors exhibit significant temporal and spatial variation; therefore, groundwater recharge estimates inevitably vary at the same scales.

Approaches to groundwater recharge estimation include water budget analysis, lysimeter and seepage meter observations [12–16], tracer tests using chloride and tritium [9,17,18], and numerical modeling [19]. In an extensive review of groundwater recharge estimation techniques, Scanlon et al. [20] emphasized the importance of choosing appropriate techniques for spatiotemporal scales to control the range and reliability of recharge estimates; they noted the difference between potential recharge estimates, which are based on surface water and unsaturated zone data, and actual recharge estimates, which are based on groundwater data. Uncertainties associated with the various approaches demand the improvement of recharge estimation techniques to increase the reliability of the results. Several recent studies have attempted to reduce the recharge estimation uncertainties using a combination of approaches [21–23], including remote sensing [24] and geographic information systems [25,26].

The groundwater level indicates the hydraulic potential resulting from the combined effects of natural and anthropogenic factors to an aquifer during groundwater movement from recharge to discharge. The estimation of groundwater recharge using the groundwater level that changes corresponding to precipitation events is called the water table fluctuation (WTF) method; this is the most direct approach based on groundwater level monitoring data [27]. Labrecque et al. [28] compared the groundwater recharge values assessed by the WTF and other methods such as water budget analysis and an analytical solution based on Dupuit–Forchheimer assumptions, and shown that the WTF method could also be applied to assess groundwater recharge in regional scales if data were available from an appropriate monitoring network.

Under the assumption that the groundwater level rises in unconfined aquifers due to the arrival of recharge water at the water table, the WTF method calculates the recharge rate \( R \) as follows [6]:

\[
R = S_y \left( \frac{dh}{dt} \right) = S_y \left( \frac{\Delta h}{\Delta t} \right)
\]

where \( S_y \) is the specific yield, \( h \) is the water table height, and \( t \) is the time. This approach is valid for events lasting for short periods of time (hours to a few days). Thus, \( R \) can be easily calculated using rainfall data and changes in water table height (\( \Delta h \)).

However, the WTF method is limited due to a number of factors. First, \( S_y \) is among the factors affecting groundwater recharge that is most difficult to measure [29–31]. \( S_y \) is not constant, but varies as a function of \( h \) [32,33]; this variability is attributed to natural heterogeneity in geologic materials, the method used to determine \( S_y \), and, most importantly, \( t \) [34]. The volume of drained water increases as the examination or observation time increases [29]; while the water in the unsaturated zone is drained or added (i.e., infiltration), the profile of the pore distribution and the size changes to compensate the loss of water which was originally stored in the pore space [35]. Second, if infiltrated
water percolates slowly and steadily, then the groundwater level will continue to decline due to natural discharge until the infiltrated water reaches the water table. Thus, if the WTF method is used, the declining groundwater level trend due to natural discharge must be removed before recharge may be calculated. That is why Labrecque et al. [28] have removed noise and calculated a more accurate Δ$h$ by applying a 5 day moving average in the groundwater hydrograph. Third, if prolonged precipitation occurs (e.g., monsoon events, which can persist for several months), then the groundwater hydrograph can extend over a longer period due to cumulative precipitation. In such cases, single precipitation events should be considered in terms of cumulative event data, rather than daily monitoring data; thus, integrated groundwater level rise maximizes the effect of recharge and minimizes the effect of relatively constant discharge.

Nimmo et al. [36] have developed the episodic master recession (EMR) method for groundwater recharge using the master recession curve with the precipitation lag-time and the WTF tolerance parameter. Most WTF approaches are considering the water-table rises corresponding to precipitations, the EMR uses the rate of water-table decline as a function of the current level after the episodic recharge event. Although focused on the estimation of recharge by episodic storm recharge, they also noticed that the recharge-to-precipitation ratio (RPR) could provide a simple way to estimate annual recharge. In fact, they found the recharge estimation by RPR and EMR had discrepancies greater than two times attributed to the high uncertainty in specific yield ($S_y$). Recently, Zhang et al. [37] proposed a precipitation recharge coefficient (PRC) to describe seasonal variation in recharge characteristics; they defined PRC as the proportion of recharge to precipitation, calculated as $PRC = \frac{R}{P}$, where $R$ is determined by the WTF method. However, they still used the daily timescale of water-table response to precipitation.

To overcome the problems with data observation frequency associated with consecutive precipitation events within a single day, Moon et al. [7] modified the WTF method to account for cumulative precipitation and corresponding groundwater fluctuation and estimate a modified recharge rate ($\alpha$) as the ratio of groundwater level rise to cumulative rainfall during extended rainy periods. They then used $\Sigma P$ to represent the actual amount of rainfall, as follows:

$$\alpha = \frac{h_1 + h_2 + \cdots + h_n}{P_1 + P_2 + \cdots + P_n} \times S_y = \frac{\Sigma h}{\Sigma P} \times S_y$$

where $h_1, h_2, \ldots, h_n$ is the groundwater level rise for each time and $P_1, P_2, \ldots, P_n$ is the precipitation at each time, where the time is expressed in days. As an additional modification, noise such as the Lisse effect should be filtered prior to calculation [38].

To date, WTF approaches have focused on the accurate estimation of recharge rate in terms of the percent of precipitation entering the river basins or aquifers in terms of the annual mean. However, for the effective management of water resources, managers require predictions of groundwater level increases after rainfall events to determine the changes to groundwater and surface water supply via baseflow discharge. Thus, recharge rates must be converted from traditional WTF data for each precipitation event to the assess current and projected groundwater levels. Due to this cumbersome approach, the WTF method is unsuitable for field applications, despite its simplicity.

In the present study, we developed a metric for the short-term prediction of groundwater level increase and the estimation of groundwater recharge following precipitation events: the apparent recharge coefficient (ARC). The ARC method is simple, intuitive, and scientifically sound for assessing groundwater recharge; thus, it is highly suitable for field application. This method is based on the modified WTF method [7], but not limited by variation in $S_y$ due to the geologic materials and covers the cumulative effects of prolonged precipitation during the rainy season. The ARC incorporates groundwater level increases due to precipitation events at specific monitoring stations, implicitly embedding the $S_y$ of the sites. The application of the ARC method will help water resource managers to improve resource development and protection measures to mitigate water hazards such as drought and flooding. Because the approach is based on the WTF method, the ARC is integrated over spatial scales up to hundreds or thousands of square meters [6].
2. Materials and Methods

2.1. Study Area

We applied the ARC method to five groundwater monitoring wells in Boeun, Chungcheong Province, and Uiryeong, Gyeongsang Province, South Korea (Figure 1). Groundwater monitoring stations B-1 and B-2 were located in Boeun, in a sub-basin of the Geum River basin in the Bocheongcheon watershed (36°21′–36°33′ N, 127°37′–127°56′ E). The terrain was mainly mountainous, with flatter areas to the west. The catchment area was approximately 553 km² and the average elevation was 264 m (maximum elevation: 1057 m) (Water Management Information System, WAMIS, http://www.wamis.go.kr). The river basin contains 12 streams and the population was approximately 34,000 in 2015. The geology of the watershed consists mainly of Daebo granite of Jurassic age (Korea Institute of Geoscience and Mineral Resources, KIGAM, http://mgeo.kigam.re.kr). The U-1, U-2, and U-3 groundwater monitoring stations were located in Uiryeong, in a sub-basin of the Nakdong River basin in the Namgang watershed (35°01′–35°37′ N, 128°00′–128°35′ E). The catchment area was approximately 1685 km² and the average elevation was 128 m (maximum elevation: ~895 m) (WAMIS, http://www.wamis.go.kr). The river basin contains 123 streams and the population was approximately 435,000 in 2015. The geology of the Namgang watershed consists mainly of igneous and metamorphic rocks (KIGAM, http://mgeo.kigam.re.kr). Lithologic logs for each site are shown in Figure 2. Wells B-1 and B-2 were covered by a sandy gravel layer, whereas wells U-1, U-2, and U-3 had low-permeability clay layers at about 5, 8, and 1 m from the surface, respectively.

According to the 30-year observation dataset (1985–2014), the average annual precipitation at the Boeun and Uiryeong weather stations were 1303 and 1315 mm and averages of 100 and 119 rainfall days per year, respectively. The monthly mean precipitation and cumulative distribution of the precipitation events in the two areas are shown in Figure 3. Precipitation events intensified during the summer (June to August) due to the summer monsoon. No significant differences in the measured precipitation were detected between the two sites; we infer that the difference in groundwater recharge following precipitation events may have been caused by variation in geologic media (e.g., thickness, composition, or texture) and therefore hydrogeological properties (e.g., permeability, porosity, or specific yield) [39].
Figure 1. Locations of the study sites, indicating the river basin boundaries and the monitoring stations: Boeun (above) and Uiryong (below) areas, respectively, in South Korea.
Figure 2. Lithologic profiles of the monitoring wells obtained from the drilling logs from the National Groundwater Monitoring Network (GIMS, http://www.gims.go.kr).

Figure 3. Monthly cumulative precipitation at the two study areas (Boeun and Uiryeong, South Korea).
2.2. Field Data Collection

We collected groundwater data from the five shallow monitoring wells (B-1, B-2, U-1, U-2, and U-3), which are part of the National Groundwater Monitoring Network (NGMN) of Korea (Table 1; National Groundwater Information Center, GIMS, http://www.gims.go.kr). At the end of 2017, the NGMN consisted of 428 monitoring stations nationwide; each station had two wells: a deep aquifer (depth: 17–198 m) and a shallow aquifer (depth: 6–30 m). Each well contained an automatic sensor and a datalogger to monitor and record the hourly groundwater level, the temperature, and the electric conductivity data, which were sent to a server once daily. Hourly precipitation data were obtained from the nearest meteorological observation network weather station to each groundwater monitoring well (Korea Meteorological Administration, KMA, http://data.kma.go.kr). Water level data and the amount of precipitation were observed in ±0.01 m and ±0.1 mm, respectively.

Table 1. Information on the monitoring wells and the hydrological properties.

| Monitoring Well | Aquifer | Elevation (m, amsl) | Depth (m) | Mean Water Level (m) | Hydraulic Conductivity (m day$^{-1}$) | Top Soil | Lag-Time (day) |
|-----------------|---------|---------------------|-----------|----------------------|---------------------------------------|----------|---------------|
| B-1             | Alluvial | 154.4               | 11.3      | 150.38 ± 0.11        | 1.16                                  | Silt, Sand | 1             |
| B-2             | Alluvial | 129.32              | 16.5      | 125.49 ± 0.17        | 0.18                                  | Sand     | 1             |
| U-1             | Alluvial | 16.57               | 10.0      | 8.20 ± 0.78          | 0.50                                  | Clay     | 1             |
| U-2             | Alluvial | 16.37               | 20.0      | 5.05 ± 0.73          | 8.08                                  | Clay     | 2             |
| U-3             | Alluvial | 73.56               | 9.5       | 69.67 ± 0.24         | 0.33                                  | Clay     | 1             |

* Monitoring data from 2005 to 2014, the annual average water level and standard deviation of the monthly mean water-level; b Result from the pumping test (National Groundwater Information Center (GIMS), http://www.gims.go.kr); c Lag time between the rainfall and each groundwater level; d above mean sea level.

3. Results and Discussion

3.1. Development of the ARC

The ARC was developed from the modified WTF [7] as a metric that could be calculated directly from the relationship between the rainfall and the water table rise. The calculation of ARC as ($R/S_y$) implicitly incorporates variation in $S_y$, which is a limitation of the traditional recharge rate ($R$) estimation (Equation (1)), as well as the effects of prolonged rainfall events and noise occurring in the recharge process.

Recent advances in groundwater level monitoring technology, using controlled time series and automatic data-logging, have improved the practicality and precision of the WTF data acquisition from long-term groundwater monitoring systems. Thus, prolonged rainfall events can be quantified independently. For example, rainfall events lasting several consecutive days or those causing continuous groundwater level rise can be treated as single events by summing the rainfall amounts. The same principle may be applied by using precipitation measured during a rainfall event to represent a corresponding continuous groundwater level rise (Figure 4). Using an automatic groundwater level monitoring system, groundwater level rise ($\Delta h$) can be calculated simply as the difference between the highest and the lowest level.
The modified WTF method [7] incorporates the concept of the amount of the total precipitation for the event rather than the daily precipitation and uses representative $S_y$ values obtained from the field tests. Because $S_y$ is difficult to measure accurately, and depends on site-specific characteristics [30,31], we propose the ARC, which implicitly incorporates site-specific characteristics of $S_y$ for the estimation of groundwater recharge as follows:

$$ARC = \frac{R}{S_y} = \frac{\Delta h}{\Sigma P}$$ (3)

When water percolating from the surface reaches the water table, subsequent water table rise ($\Delta h$) is controlled by both $R$ and $S_y$ simultaneously. The ARC is the linear regression coefficient of the relationship between the precipitation and the groundwater level rise during multiple events. Thus, groundwater recharge estimates obtained using the ARC were not limited by the variation of the $S_y$ of geologic materials or the effects of prolonged rainfall because these factors were subsumed within the coefficient.

We performed a linear regression of $\Delta h$ and $\Sigma P$ under the following three assumptions: (a) if barometric effects such as Lisse effects were removed from the groundwater level fluctuation data, then only the groundwater level rise during rainfall events contributes to the recharge process; (b) the groundwater level at the time of a rainfall event is an appropriate reference value for calculating the groundwater level rise during that event; (c) even small amounts of precipitation can influence the WTF. However, small rainfall events may not allow percolation through the vadose zone to reach the water table, or may be insufficient to compensate for groundwater level decline due to long-term natural discharge. In such cases, the groundwater level changes due to precipitation events that could be zero or negative, causing deviation from the linear regression model.

3.2. Steps to Calculate ARC for Monitoring Stations

The detailed steps for estimating ARC values are as follows:

**Step 1:** The identification of each precipitation event. A single precipitation event was defined as a period of continuous rainfall [7]. However, breaks in the precipitation data shorter than 24 h were discounted in this study.

**Step 2:** The determination of the groundwater level rise due to a rainfall event. After the precipitation events were identified, groundwater level rises due to precipitation recharge were calculated by subtracting the lowest groundwater level after the event began from the highest level recorded during the 48 h following the end of the precipitation event. The delay time was based on
the results of correlation analysis in the previous study [40], which used daily precipitation and daily mean water-level for 3–5 years.

**Step 3:** The classification of recharge characteristics based on seasonal changes in precipitation events. The calculated groundwater level rises due to precipitation events were grouped seasonally (spring: March–May; summer: June–August; autumn: September–November; winter: December–February), based on the seasonal variation in temperature and precipitation in Korea, and their effects on soil moisture and vegetation. The potential groundwater level increase (ARC) due to precipitation events was calculated for each season by performing a linear regression of $\Delta h$ and $\Sigma P$.

**Step 4:** The removal of the significant outliers and re-estimation. Outliers are defined as observations that show spreading greater than three standard deviations from the regressive curve. Outliers were removed to obtain representative mean values of multiple events; they may be caused by Lisse effects, groundwater pumping for agricultural activity, or insufficient precipitation. The ARC was then re-estimated based on the modified dataset. Because groundwater level rise (mm) is divided by total precipitation (mm) for each event, the ARC is expressed in the dimensionless value of (mm/mm).

### 3.3. Calculation of the ARC in Field Conditions

The groundwater level and precipitation data were analyzed for the 10 year period from 2005 to 2014 (Figure 5). Groundwater level fluctuations at the five wells showed seasonal variation, with peaks gradually increasing annually during the period May–September, corresponding to the wet season. Groundwater level rise and precipitation were qualitatively correlated, indicating that precipitation was a major factor influencing groundwater recharge. The annual range of groundwater level fluctuation was 0.84 ± 0.24 and 1.59 ± 0.59 m at the Boeun stations and 4.96 ± 1.11, 8.09 ± 2.61, and 2.06 ± 0.62 m at the Uiryeong stations, respectively. In Uiryeong, where a thick clay layer was found in the upper part of the logging data, higher increases in groundwater levels corresponded to precipitation events, probably due to lower $S_y$. The groundwater level peaks for Boeun and Uiryeong were similar in shape, but the magnitude of the variation was smaller at Boeun.

The slope of the relationship between the groundwater level rise and the total precipitation during rainfall events from 2005 to 2014 was used to determine the ARC (Figure 6). Seasonal linear trends were calculated using best-fit lines and their variability was determined using the correlation coefficient ($R^2$). The average $R^2$ values of the five wells ranged from 0.29 to 0.84 for the 10 year study period, at 0.78, 0.71, 0.48, and 0.58 for summer, autumn, spring, and winter, respectively ($p < 0.05$, Figure 6; Table 2).

### Table 2. Seasonal variation in the apparent recharge coefficient at each monitoring well.

| Well | Parameter | Spring | Summer | Autumn | Winter | Mean | StdDev ** |
|------|-----------|--------|--------|--------|--------|------|----------|
| B-1  | ARC       | 2.5    | 2.18   | 2.42   | 2.38   | 2.37 | 0.14     |
|      | $R^2$     | 0.71   | 0.84   | 0.84   | 0.70   |      |          |
| B-2  | ARC       | 6.76   | 2.63   | 4.47   | 12.91  | 6.69 | 4.48     |
|      | $R^2$     | 0.46   | 0.76   | 0.67   | 0.75   |      |          |
| U-1  | ARC *     | 10.32  | 6.19   | 5.75   | 9.91   | 8.04 | 2.41     |
|      | $R^2$     | 0.29   | 0.72   | 0.62   | 0.33   |      |          |
| U-2  | ARC       | 7.38   | 24.5   | 15.22  | 7.25   | 13.59| 8.17     |
|      | $R^2$     | 0.31   | 0.83   | 0.60   | 0.33   |      |          |
| U-3  | ARC       | 8.81   | 4.37   | 6.22   | 13.67  | 8.27 | 4.04     |
|      | $R^2$     | 0.65   | 0.77   | 0.83   | 0.77   |      |          |

* ARC and ** StdDev denote the apparent recharge coefficient and the standard deviation, respectively.
Figure 5. Groundwater level changes at the five monitoring wells from 2005 to 2014. (a) B-1 and (b) B-2 are located in the Boeun area, and (c) U-1, (d) U-2, and (e) U-3 are located in the Uiryeong area.
Figure 6. Relationships between the precipitation and the groundwater level at (a) B-1, (b) B-2, (c) U-1, (d) U-2, and (e) U-3 during the period 2005–2014.

At all the monitoring locations, summer ARC values were well correlated with the highest $R^2$ values. Summer and autumn $R^2$ values were noticeably greater than those of spring and winter. During spring, the agricultural activities that require groundwater affect groundwater level rise due to rainfall events. Although snowmelt is a major groundwater recharge mechanism in winter [41,42], continuous low temperatures (<0 °C) can freeze land surfaces, leading to interference with snowmelt recharge [43]. At the U-1 and U-2 wells, low $R^2$ values, ranging from 0.29 to 0.33 for winter and spring, were attributed to the thicker clay layers at the surface than at other locations (Figure 2).

The ARC values varied significantly among monitoring wells, with means ranging from 2.37 to 13.59 (mm/mm); this variation reflected the complicated effects of hydrological properties, such as the specific yield ($S_y$) of geologic materials. The B-1 well (Table 2; Figure 6a) showed similar trend lines in all seasons, with no significant seasonal difference in ARC ($R^2$: 0.70–0.84). The mean ARC was 2.37 with a standard deviation of 0.14 (5.9%), indicating that the groundwater level rise was well predicted from the weather monitoring data in all seasons and thus water resource management could be improved based on predicted changes in water reserves. At other monitoring locations, the groundwater level rise was also well predicted in summer and autumn, with $R^2$ values ranging from...
0.60 to 0.84. Therefore, the ARC can be applied in most areas with a monsoon climate, where summer and autumn are the principal seasons for groundwater recharge from precipitation. Nevertheless, the standard deviation of monitoring wells other than B-1 ranged from 29.9 to 66.9% of the mean ARC among seasons, suggesting that the ARC should be considered as a site-specific, rather than basin-scale, hydrological property.

3.4. Validation of Groundwater Recharge Predictions Obtained Using the ARC

Using ARCs obtained from the 2005 to 2014 data, groundwater level rises for 2015 and 2016 were calculated based on weather data and plotted against the field observations. Then, the reliability of the ARC approach was evaluated using the root mean square error (RMSE) between these observed and estimated values (Figure 7).

Figure 7. Estimated and observed groundwater level rise at the monitoring wells (a) B-1, (b) B-2, (c) U-1, (d) U-2, and (e) U-3 determined using the groundwater level and the precipitation time series data for 2015–2016 to validate the linear regression of groundwater level rise and precipitation.
The RMSE values ranged from 0.03 to 0.34 m. The B-1 well had the lowest RMSE (0.03 m), indicating that the predicted values were close to the observed values. The B-2 and U-3 wells had RMSE values of 0.09 and 0.14 m, respectively. By contrast, higher RMSE values (0.21 and 0.34 m) were obtained for wells U-1 and U-2, respectively. These wells were installed in areas with thicker clay layers at the surface. Because clay has low permeability, precipitation recharge is very low during the short period following rainfall events, causing interference with groundwater level responses.

For example, water table rise is generally a response to precipitation, via percolation through the unsaturated zone; its magnitude must be adjusted by the rate of natural discharge, which causes water table decline, to avoid underestimations. However, if percolation is deterred by materials with low permeability, such as clay, then the groundwater recharge and subsequent groundwater level rise will be delayed. In such cases, the separation of the groundwater level increases based on corresponding rainfall events can be complicated, because the ARC method is based on events occurring within a 48 h window. For example, if consecutive precipitation events occur during a 3 day interval and percolation through the clay layer requires longer than 3 days, then the ARC approach would count both rainfall events. However, the groundwater level rise corresponding to the first event will be lower than predicted, which is the best fit among multiple cases. The groundwater level rise in response to the second event will be much higher than predicted due to accumulated percolated water from the first and second events. These conditions were present at wells U-1 and U-2, where thick clay layers covered the soil.

In summary, RMSE values less than 0.34 m indicate that the ARC approach is suitable for predicting groundwater level rise due to rainfall events. This method has limited applicability in areas with impermeable layers, which can delay recharge. The ARC is spatially and temporally variable, and should therefore be considered as a site-specific hydrogeological characteristic for use with long-term monitoring data. In a regional groundwater monitoring network, the regional recharge due to rainfall events can be estimated rapidly and directly at each monitoring station, improving water resource management for the region.

Recent reports of groundwater baseline surveys for the Boeun and Uiryeong areas [44,45] provided average groundwater recharge rate estimates of 0.13 (obtained using groundwater level decline curve analysis) for Boeun and 0.17 (obtained using the NRCS-CN method [46]) for Uiryeong. To validate our results, we calculated the groundwater recharge rates using ARCs and compared these to those reported in these surveys. The $S_y$ values for these areas (adapted from Moon et al. [7]) were 0.0134 and 0.0596, respectively.

In Boeun, the ARC-based recharge rates ranged from 0.13 to 0.77 (average: 0.27), which was more than 2-fold that estimated in the survey [45] using groundwater level decline analysis, probably due to the exceptionally high values of 0.77 in winter and 0.40 in spring at the B-2 monitoring station. Subsequently, the high recharge rate estimated by the ARC method can be understood as a site-specific characteristic of the B-2 station, which has a sandy gravel composition at the surface (Table 3). In Uiryeong, groundwater recharge rates calculated using the ARCs ranged from 0.06 to 0.33 with an average of 0.13. Since the NRCS-CN method assumes that all infiltrated water contributes to recharge, groundwater reaching the water table would therefore be overestimated, and thus, the slightly lower recharge rates in this study seem reasonable (Table 3).
Table 3. Groundwater recharge rates calculated from the apparent recharge coefficients of each monitoring well.

| Well | Parameter | Spring | Summer | Autumn | Winter | Mean | StdDev *** |
|------|-----------|--------|--------|--------|--------|------|----------|
| B-1  | ARC *     | 2.50   | 2.18   | 2.42   | 2.38   | 2.37 | 0.14     |
|      | R **      | 0.15   | 0.13   | 0.14   | 0.14   | 0.14 | 0.01     |
| B-2  | ARC *     | 6.76   | 2.63   | 4.47   | 12.91  | 6.69 | 4.48     |
|      | R **      | 0.40   | 0.16   | 0.27   | 0.77   | 0.40 | 0.27     |
| U-1  | ARC *     | 10.32  | 6.19   | 5.75   | 9.91   | 8.04 | 2.41     |
|      | R **      | 0.14   | 0.08   | 0.08   | 0.13   | 0.11 | 0.03     |
| U-2  | ARC *     | 7.38   | 24.50  | 15.22  | 7.25   | 13.59| 8.17     |
|      | R **      | 0.10   | 0.33   | 0.20   | 0.10   | 0.18 | 0.11     |
| U-3  | ARC *     | 8.81   | 4.37   | 6.22   | 13.67  | 8.27 | 4.04     |
|      | R **      | 0.12   | 0.06   | 0.08   | 0.18   | 0.11 | 0.05     |

* ARC, ** R and *** StdDev denote the apparent recharge coefficient, the groundwater recharge rate calculated from the ARC and the standard deviation, respectively.

4. Conclusions

In this study, we developed a simple and direct method to assess groundwater recharge, using the relationship between precipitation events and the corresponding groundwater level rises. The ARC ($R/S_y$) at each groundwater monitoring station was calculated as the slope of the regression line of cumulative groundwater level rises and the total amount of precipitation events for 10 years. Because the ARC method uses the observations of groundwater and precipitation, it is sensitive to the frequency of observation and the amount of available monitoring data. The estimation of groundwater recharge using the traditional WTF method has been limited due to variation in $S_y$. However, because this parameter is embedded in the ARC, the uncertainty attributed to $S_y$ would be represented as that of the ARC. Consequently, the ARCs showed site-specific characteristics with seasonal variation in the study area, probably reflecting the effect of the monsoon climate in temperate regions. Generally, the ARCs in wet seasons (summer and autumn) showed better correlation between precipitation and groundwater level rise, with higher $R^2$ values than in dry seasons (winter and spring). However, in areas with thick impermeable layers such as clay materials at the unsaturated zone, recharge can be delayed, causing errors in the estimation of apparent recharge. Agricultural activities dependent on groundwater resources in spring and frozen land cover in winter can also interfere with groundwater level responses to precipitation, causing deviations from the best-fit line.

Groundwater recharge is a process with spatial and temporal variations. Using the ARC method also shows the spatio-temporal variations in recharge estimation. However, embedding the site-specific characteristic of $S_y$ and the effects of prolonged precipitation events could make the results of recharge estimation from time-series monitoring data much simpler and easier. Using the ARC method, rechargeable water from rainfall events can be calculated simply and quickly by predicting the corresponding groundwater level rise. This method can be used to predict changes in the groundwater reservoir for selected regions or basins immediately after precipitation events. As suggested by Labrecque et al. [28], in regions where groundwater monitoring networks have accumulated long-term groundwater level data, the ARC method can provide better options for regional water resource management, allowing improved decisions for allocating and developing water resources for residents and industry, as well as groundwater-dependent ecosystems.

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