Seasonal control of spatial distribution of soil moisture on a steep hillslope
Xiaoyi Dong, Eunhyung Lee, Yongseok Gwak and Sanghyun Kim

ABSTRACT
Spatio-temporal variation in soil moisture plays an important role in hydrological and ecological processes. In the present study, we investigated the effect of environmental factors on variation in soil moisture at a hillslope scale. The relationships among various environmental factors, including soil properties, topographic indices, and vegetation of a humid forest hillslope, and soil moisture distributions were evaluated based on soil moisture data collected at 18 sampling locations over three seasons (spring, rainy, and autumn) at depths of 10, 30, and 60 cm. In order to evaluate the multi-dimensional data sets without the interaction among factors, the principal component regression (PCR) model was applied to identify the factors controlling the spatio-temporal variation in soil moisture. The effects on soil texture and topography were significant in spring. In addition, clay and sand appeared as critical control factors for the study area in all seasons. The transitional control pattern in the soil moisture profile indicated that the control varied depending on features, such as total amount, intensity, and duration, of rainfall events in spring and during the rainy season. The transitional control pattern for autumn showed that vegetation and local slope controlled transitions in topography.

Key words | hydrological processes, principal component regression, probability density function, soil moisture, spatio-temporal variability

INTRODUCTION
The spatial patterns and temporal variation in soil moisture play a significant role in hydrological processes such as infiltration and evapotranspiration at the hillslope scale (Tromp-van Meerveld & McDonnell 2006; Brocca et al. 2012; Zheng et al. 2016). In order to better understand the process of soil moisture variation, many approaches have been attempted, such as geostatistical analysis and correlation analysis with the important physical factors, including soil properties (Famiglietti et al. 2008), topographic attributes (Qiu et al. 2001), soil depth (Gwak & Kim 2017), and vegetation (Gerrits et al. 2010). Most studies only indicate one or two significant factors, whereas only a few studies have concentrated on the interaction between diverse factors and the spatio-temporal variation in soil moisture.

Moreover, previous research emphasized that precipitation events were significantly correlated with soil moisture dynamics (Famiglietti et al. 1998). Brocca et al. (2009) indicated that the antecedent soil moisture was strongly connected to the hydrological response. The precipitation showed a strong influence on various physical controls of soil moisture (Gaur & Mohanty 2013) on an extent scale. Further analysis was conducted to find the main controls that influenced variations in soil moisture, both during and after the rainfall period (Kim & Barros 2002). Some studies explained the relationship between soil moisture variability and the controlled factors from a long-term perspective (Perry & Niemann 2008). In order to better understand the spatial and temporal variation in soil moisture, multivariate statistical methods were used to identify the primary factor of soil moisture variation. Yang et al. (2012) applied a canonical correspondence analysis to find significant environmental factors that affected soil moisture variations at different depths in the semi-arid Loess Plateau, China. Although some studies showed that several methods assume the factors affecting soil moisture dynamics (Kim 2012; Liao et al. 2017), the multiple relationship among environmental attributes is hardly configured. In order to solve soil moisture control issues of the multiple

interactions among environmental attributes, a principal component regression (PCR) model was used in the present study. The PCR model is a method combining principal component analysis (PCA) with multiple linear regressions (Reiss & Ogden 2007; Cho et al. 2009). PCA was used to characterize the spatio-temporal pattern of soil moisture at a hillslope (Martini et al. 2017).

In the present study, the identification of control factors was explored for the spatio-temporal variation of soil moisture, which provides a better building block for soil moisture prediction on a hillslope. Soil moisture content was monitored at depths of 10 cm, 30 cm, and 60 cm every 2 h from March 2016 to November 2016 on a forested steep hillslope. In addition, the environmental factors, including topographic indices, soil properties, soil depth, and vegetation, were measured and evaluated. The PCR model was used to assess the correlation of environmental factors with spatio-temporal variations in soil moisture in three different seasons and to identify soil moisture controls during transitional periods in the rainfall event.

Therefore, the objectives of this study were as follows: (1) to determine the relationship between the multiple factors and the spatio-temporal variation in soil moisture for different seasons at three depths by the application of PCR; (2) to identify environmental controls for soil moisture redistribution by the soil depth profile depending on the season; and (3) to characterize the transitional control patterns of soil moisture profile during rainfall events.

MATERIALS AND METHODS

Study area

The study area is located at the Chongmichun catchment in Chungcheongbuk-do, South Korea (37°02′14.0″ N, 127°39′50.8″ E) (Figure 1). The research site belongs to a humid forest, with a mean annual temperature of approximately 11.5 °C. The mean annual precipitation is approximately 1,400 mm. The area of the hillslope studied is approximately 2,047 m², which has a gentle slope and convergent terrain in a downhill direction. The average slope of the hillside is 16.3°, and the elevation above the sea level of the study area is approximately 400 m.

Figure 1 | The soil moisture monitoring hillslope located at the Chongmichun watershed.
soil texture mainly consists of sand, silt and clay, and the soil porosity ranges between 46.7% and 53.4%. The soil depth ranges from 0.2 to 1.1 m. The vegetation is composed of deciduous (95%) and coniferous (5%) canopies.

Data acquisition

Time series data on soil moisture were obtained at 18 locations along four transects on the hillslope in 2016 by using time-domain reflectometry (TDR). At each location, time series data on soil moisture were acquired by sensors at 10 cm, 30 cm, and 60 cm depths (Figure 1). Three waveguide sensors were installed for the soil depth profile inserted parallel to the upslope direction. The soil moisture content was recorded at 2 h intervals for approximately nine months (from March to November) by a TDR system over three seasons (spring, summer, autumn). The rainfall data were collected at 10 min intervals using a rain gauge (16.98.47, Eijkelkamp) at each site.

The condition of topographic attributes was measured by a digital elevation model. According to the topography analysis, the wetness index could be calculated by \( \ln\left(\frac{a}{\tan \beta}\right) \), where a is the upslope contributing area and \( \tan \beta \) is derived from the local slope. The soil depth was measured using iron poles. The soil type was determined based on the classification system defined by the United States Department of Agriculture (USDA). The bulk density was evaluated by soil samples from measured points. In addition, the weighted basal area (WBA), which is expressed as the effect of the trees on the soil moisture, was used to evaluate the effect of trees on the soil moisture measurement points (Tromp-van Meerveld & McDonnell 2006).

Analysis method

PCR was used to analyze the soil moisture data sets. In other words, we used principal components (PCs) as the operator for the regression analysis. The environmental attributes for soil moisture variation were analyzed by means of PCA. PCA was used for reducing the independent components of the multi-dimensional data set in terms of the least linear combinations. The data matrix was composed of the number of soil moisture measuring points (n) and environmental factors (q). In order to compute PCs from the data set, we used the spectral decomposition of covariance (S):

\[
S = V \Lambda V^T
\]

where \( \Lambda = \text{diag}(\lambda_1, \ldots, \lambda_j, \ldots, \lambda_q) \), which is a diagonal matrix that contains eigenvalues \( (\lambda_j) \), and \( V = (v_1, \ldots, v_j, \ldots, v_q) \), which is an orthogonal matrix whose columns \( (v_j) \) are eigenvectors. The dominant environmental factors were determined by the eigenvalues of the PCs. The first PC had the highest explanation capability among all the PCs, which was calculated by multiplying the eigenvectors and data matrix, as follows:

\[
\begin{align*}
\begin{bmatrix}
Y_{11} \\
\vdots \\
Y_{n1}
\end{bmatrix}
&= 
\begin{bmatrix}
x_{11} & \cdots & x_{1q} \\
\vdots & \ddots & \vdots \\
x_{n1} & \cdots & x_{nq}
\end{bmatrix}
\begin{bmatrix}
v_{11} \\
\vdots \\
v_{q1}
\end{bmatrix} \\
&= X V^T
\end{align*}
\]

Combinations of multivariate environmental factors were expressed in terms of eight PCs throughout the PCA. All PCs were used to construct a regression model, and were statistically determined as significant PCs based on the criterion of \( p < 0.05 \). The PCR model uses the identified PCs as dependent variables for the prediction of spatial distribution of soil moisture to delineate the transitional behavior of controls.

RESULTS

Rainfall and soil moisture time series

The rainfall and time series of the mean soil moisture at depths of 10 cm, 30 cm, and 60 cm in the study area between March and November 2016 are presented in Figure 2. These mean soil moisture values were 15.6–34.7%, 18.9–35.3%, and 22.5–37.6% at 10 cm, 30 cm, and 60 cm, respectively. The mean soil moisture content increased with soil depth.

Figure 2 | Time series of soil moisture means and rainfall at depths of 10 cm, 30 cm, and 60 cm.
since evaporation had varied impacts on different soil depth profiles. The mean soil moisture content was highest at 60 cm, because this depth had a higher capacity to hold water with less root uptake from the vegetation than shallower depths.

Figure 2 also shows seasonal patterns, attributable to seasonal differences in rainfall and eco-hydrological activities such as evapotranspiration, in the soil moisture responses. The soil moisture content was relatively low in spring due to a lower level of precipitation. The mean soil moisture content increased in the rainy season as a prompt response to frequent rainfall events. The distribution of the soil moisture pattern tended to be stable in autumn season with less rainfall. There were distinct relationships between rainfall and soil moisture distributions during the three distinct seasons (spring, rains, and autumn).

Identification of seasonal environmental controls

We had measured and calculated various environmental factors affecting the spatial distribution of soil moisture. The topographic factors were expressed in terms of local slope (tan\(\beta\)), contributing area (CA), and wetness index (WI; Quinn et al. 1999). The WBA, which is the index for vegetation (Liang et al. 2017) and soil properties, was expressed as the percentage of sand, clay, and silt. The composition of pore and soil structure were expressed using bulk density, which was measured only at a depth of 10 cm. To configure the relationship between soil moisture distribution and its controls, the correlation structure among different factors needs to be considered. The PCs of environmental factors should be identified to perform the analysis between soil moisture and various environmental factors.

Table 1 presents the delineated principal components for PCR, and PC1 to PC8 represent the PCs identified for different control combinations. The numbers in Table 1 are the eigenvectors and represent the importance of each PC. As illustrated in Table 1, the environmental controls with eigenvectors indicate the most significant controls in each PC. For example, 0.434 of WI and 0.432 of CA were the biggest and second eigenvectors in PC2 at 10 cm depth, and 0.730 of WBA and 0.544 of tan\(\beta\) were those for PC3 at 10 cm depth. Table 1 shows that the compositions of sand, silt, and clay tend to commonly appear as a PC for soil texture, and the combination of WI and CA represents the effect of topography. In addition, other controls, such as SD, WBA, and tan\(\beta\), frequently appeared simultaneously in the PCs. The seasonal differences in rainfall and vegetation activity introduce non-stationarity in soil moisture redistribution, as well as high nonlinearity in hydrologic responses on the hillslope. In other words, the contribution of environmental factors to soil moisture redistribution can vary seasonally (Talib & Randhir 2017).

We evaluated the seasonal effect of environmental control on soil moisture based on the identification of significant factors for each season. The number of PCs and the representative environmental factors can be represented depending on the season and depth.

<table>
<thead>
<tr>
<th>Depth</th>
<th>10 cm</th>
<th>30 cm</th>
<th>60 cm</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC1</td>
<td>Clay</td>
<td>−0.425</td>
<td>WI</td>
<td>0.492</td>
</tr>
<tr>
<td></td>
<td>Sand</td>
<td>0.415</td>
<td>CA</td>
<td>0.477</td>
</tr>
<tr>
<td>PC2</td>
<td>WI</td>
<td>0.434</td>
<td>Silt</td>
<td>0.576</td>
</tr>
<tr>
<td></td>
<td>CA</td>
<td>0.432</td>
<td>Clay</td>
<td>0.503</td>
</tr>
<tr>
<td>PC3</td>
<td>WBA</td>
<td>0.730</td>
<td>WBA</td>
<td>0.690</td>
</tr>
<tr>
<td></td>
<td>tan(\beta)</td>
<td>0.544</td>
<td>tan(\beta)</td>
<td>0.515</td>
</tr>
<tr>
<td>PC4</td>
<td>BD</td>
<td>−0.903</td>
<td>Sand</td>
<td>−0.727</td>
</tr>
<tr>
<td></td>
<td>WI</td>
<td>0.238</td>
<td>SD</td>
<td>0.575</td>
</tr>
<tr>
<td>PC5</td>
<td>SD</td>
<td>−0.900</td>
<td>SD</td>
<td>−0.676</td>
</tr>
<tr>
<td></td>
<td>tan(\beta)</td>
<td>−0.312</td>
<td>Sand</td>
<td>−0.562</td>
</tr>
<tr>
<td>PC6</td>
<td>tan(\beta)</td>
<td>0.635</td>
<td>tan(\beta)</td>
<td>0.642</td>
</tr>
<tr>
<td></td>
<td>WBA</td>
<td>−0.586</td>
<td>WBA</td>
<td>−0.567</td>
</tr>
<tr>
<td>PC7</td>
<td>Clay</td>
<td>0.807</td>
<td>Clay</td>
<td>0.730</td>
</tr>
<tr>
<td></td>
<td>Silt</td>
<td>−0.475</td>
<td>Silt</td>
<td>−0.665</td>
</tr>
<tr>
<td>PC8</td>
<td>WI</td>
<td>0.734</td>
<td>WI</td>
<td>0.734</td>
</tr>
<tr>
<td></td>
<td>CA</td>
<td>−0.669</td>
<td>CA</td>
<td>−0.669</td>
</tr>
</tbody>
</table>
Table 2 presents the results of PC1 to PC8 based on the PCRs between soil moisture and environmental controls. Ignoring the seasonal difference in soil moisture at the depth of 10 cm made PC6 and PC5 the primary principal components, which were mainly composed of SD, tanβ, and WBA as environmental controls. The soil moisture at a shallow depth (10 cm) can be significantly affected by vegetation activity, and the local surface flow can be affected by the slope. Moreover, infiltration and exfiltration processes are determined by soil depth, which affect the soil moisture at a shallow depth. The relationship between soil moisture and environmental controls appeared to be the most significant at a depth of 30 cm. Significant PCs were found in 100%, 94%, and 95% of the periods in the spring, autumn, and rainy seasons, respectively. Furthermore, multiple PCs were found in the spring, rainy, and autumn seasons. The compositions of PCs were more diverse at a depth of 30 cm than at depths of 10 and 60 cm. Seasonal dominance in PCs was most apparent at the 30 cm depth, representing strong seasonal interaction between soil moisture and its controls.

As presented in Table 2, PC2, PC6, and PC8 were the dominant PCs for explaining soil moisture at the 30 cm depth for the spring, rainy, and autumn seasons, respectively. The effects of vegetation on soil moisture at the 10 cm depth disappeared, and soil texture and topographic controls increased at a depth of 30 cm during spring. However, the dominance in PC6 at the 30 cm depth during the rainy season was similar to that of the depth of 10 cm, which can be explained by the high rainfall in the rainy season, which causes a deeper infiltration than that seen in spring. The relationship between soil moisture and controls was least significant at a depth of 60 cm, which was indicated by the meaningful PCs found in 11%, 6%, and 9% of the periods in the spring, autumn, and rainy seasons, respectively. PC1 was the most significant in all seasons, indicating that clay and sand were important. The effects of topographic and vegetation controls were weak at a soil depth of 60 cm, and the impact of soil texture is greater than that of other factors.

**DISCUSSION**

**Transitional control patterns of soil moisture profile**

The soil moisture control can be defined as the influencing factor for the spatial and temporal redistribution of soil moisture, which is the attribute of environmental components, such as topography, soil, and vegetation. Soil moisture controls can be varied for a rainfall event pattern and its controls can be changed directly due to rainfall generation. Therefore, the transitional controls can be divided into the following three periods: prior to, during, and post-rainfall events. Since the dominant hydrological process is vertical infiltration, its dominance in the controls and transitional patterns should be expressed in the soil depth profile. Furthermore, infiltration and exfiltration depend strongly on
rainfall patterns and the development of vegetation. Therefore, seasonal variations in soil moisture control must be considered.

Table 3 presents the PCR results for transitional control patterns at 10 cm, 30 cm, and 60 cm in the three different seasons. The PC patterns for the first of these depths showed that PC6 ($\tan\beta$ and WBA) was the dominant component for the period prior to rainfall events in all seasons. This changed to PC5, PC7, and PC1 in the periods during and post-rainfall events, as the season shifted from spring to autumn (Table 3). This means that soil depth and $\tan\beta$ began to have a higher impact than vegetation during rainfall events in the spring, with a similar trend occurring before rainfall events for soil texture during the rainy and autumn seasons, at a depth of 10 cm. Transitional controls at a depth of 30 cm showed different patterns too at 10 cm, although one similarity was that the PC prior to rainfall events was PC6, which changed to PC2 during the spring and rainy seasons (Table 3). However, in the late rainy and autumn seasons this change involved PC8 or PC3 post-rainfall events, which indicates that topographic controls such as wetness index and contributing area are important. This suggests that while local slope directly or indirectly influenced the soil moisture at a depth of 10 cm, that of the depth of 30 cm was determined by the development of subsurface flow, which can be correlated to the upslope contributing area or wetness index. Variations in soil moisture at 60 cm were negligible with little rainfall, and there was a relationship between soil moisture and its controls in the autumn. The impact of the texture of soil (PC1) such as clay and sand on the soil moisture at 60 cm was significant during spring and the rainy season. There was also an impact from vegetation (PC5) in spring, and the appearance of the impact of soil depth (PC4) during the rainy season indicates the effect of substantial rainfall and its infiltration into the soil layer.

### General patterns of transitional control

Variations in soil moisture can be understood in terms of spatial variation without considering depth profiles. In other words, seasonal transitional control patterns can be captured better through the general patterns in soil moisture, regardless of its depth.

General transitional control patterns during spring and the rainy season varied from PC5 for periods prior to rainfall events to PC5 for post-rainfall events (Table 4). This indicates that the soil moisture controls changed with the amount of rainfall and varied, during rainfall events and subsequent short periods of recession, depending on features such as total amount, intensity, and duration of the former. The local slope ($\tan\beta$) and impact of vegetation...
(WBA) are the two main factors affecting periods between rainfall events; combinations of soil textures such as clay and sand and topographic factors (WI, CA) were controls during rainfall events (Table 4). Transitional controls during the autumn appeared frequently in WI and CA data, indicating that the transition between vegetation and local slope has a greater impact than topography. PC5 made up a substantial portion of the general transitional control event in the autumn, indicating that local slope and vegetation are the primary controls of soil moisture for all seasons (Table 4).

**Temporal soil moisture response to transitional rainfall events**

Figure 3 shows the rainfall and soil moisture for transition control patterns at a depth of 10 cm for periods prior to, during, and post-rainfall events (see Table 3). During the rainfall events, the soil moisture content increased with the precipitation intensity, and the highest soil moisture content with the maximum precipitation. After the rainfall events, the variability in soil moisture declined slightly and tended towards the more stable. The main controls during the period prior to rainfall events were tanβ and vegetation, as shown in Table 3. After the rainfall, soil depth and tanβ became the main controls. This means that the effect of soil depth is notable for variances in the soil moisture during the transition between wet and dry conditions.

The soil moisture variability at 30 cm was more complicated than that at 10 cm (Figure 4). As shown in Figures 3 and 4, the variation in soil moisture between the two different depths was similar for the period prior to rainfall events. The former varied slightly as precipitation began during the antecedent precipitation period, and soil properties are the main influence on the spatial variability of soil moisture (Table 3). During the intensive rainfall period, the soil moisture patterns varied with rainfall duration and the topographic indices (WI, CA) became the transition controls (Table 3). This tendency to variability decreased significantly post-rainfall events, and the environmental controls reverted to those from the prior period. The spatio-temporal variability in soil moisture was more apparent at 30 cm than at
10 cm, indicating that it is affected primarily by rainfall at the former depth, but partially governed by hillslope hydrological processes such as subsurface flow at the latter.

Figure 5 presents the soil moisture response at 60 cm for the sequential period shown in Figures 3 and 4. During the rainfall event, variations in soil moisture were also influenced by the rainfall. However, the relationship between rainfall and soil moisture was highly nonlinear and spatially distinctive. Soil moisture content was similar in periods both prior to and post-rainfall events, as the properties of soil (clay, sand) in the area were related to patterns in soil moisture dynamics at deep soil layers (Table 5). The impact of soil depth and local slope was important to the variance in soil moisture during rainfall events.

**Probability density function for transitional soil moisture**

The spatial distribution of soil moisture for the transitional periods of rainfall events can be characterized by identifying the probability density function (PDF) for soil moisture measurements. In order to delineate the best goodness of fit for the soil moisture data sets, the Anderson–Darling test was introduced; the soil moisture data sets for periods prior to, during, and post-rainfall events were then tested using the widely adapted Gumbel, Frechet, Weibull, Log-Pearson 3, Lognormal, Normal, Gamma, and Exponential hydrological distributions. As Table 5 shows, the principal component changed more than two times for periods during rainfall events and the corresponding fitted PDFs were obtained.

PDFs for soil moisture were found to show Normal and Lognormal distributions for periods prior to and post-rainfall events, while the Gumbel distribution appeared in spring due to the rainfall generated. This can be explained

<table>
<thead>
<tr>
<th>Season</th>
<th>Date (m/d/h)</th>
<th>PDF</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>From</td>
<td>To</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spring</td>
<td>04-16 22</td>
<td>04-17 22</td>
</tr>
<tr>
<td></td>
<td>04-12 22</td>
<td>04-22 00</td>
</tr>
<tr>
<td></td>
<td>05-15 06</td>
<td>05-17 04</td>
</tr>
<tr>
<td></td>
<td>05-23 00</td>
<td>05-25 00</td>
</tr>
<tr>
<td>Rainy</td>
<td>07-01 00</td>
<td>07-03 00</td>
</tr>
<tr>
<td></td>
<td>07-03 06</td>
<td>07-06 06</td>
</tr>
<tr>
<td></td>
<td>07-11 10</td>
<td>07-12 20</td>
</tr>
<tr>
<td></td>
<td>07-15 10</td>
<td>07-17 20</td>
</tr>
<tr>
<td></td>
<td>08-30 22</td>
<td>08-31 22</td>
</tr>
<tr>
<td>Autumn</td>
<td>09-01 16</td>
<td>09-02 16</td>
</tr>
<tr>
<td></td>
<td>09-16 04</td>
<td>09-18 04</td>
</tr>
<tr>
<td></td>
<td>11-10 00</td>
<td>11-12 00</td>
</tr>
</tbody>
</table>
by the dominant control prior to the rainfall events tending to change from the impact of vegetation and local slope (PC5) to the significant topographic control of contributing area (PC1), which caused soil moisture to become more concentrated, changing the PDF of soil moisture from Normal to Gumbel distribution. The sequential distribution of the PDF was relatively simple during events in April, but tended to become more complicated in May due to the increased development of vegetation.

The most diverse distributions in the soil moisture PDFs were found during the rainy season, as shown in Table 5. The high frequency of rainfall generation and a high rainfall intensity influenced the redistribution of soil moisture, meaning that the impact of antecedent soil moisture conditions during the rainy season was much greater than in the two dry seasons. Normal or Gamma distributions were found temporarily during short periods of highly intense rainfall, which can be explained by the sudden instant increase in soil moisture at all points, even before the soil moisture redistribution began along the hillslope. The PDFs for the autumn were simple due to the low number of rainfall events. They can be characterized as either Gumbel or Weibull distributions, which are the two extremes. As shown in Table 5, the impact of topography (such as the WI) or contributing area was dominant, and the soil moisture distribution addressed the topographic features of the hillslope spatially, reaching the minimum at the highest upslope point and the maximum at the lowest downslope point.

**CONCLUSION**

This study showed that spatio-temporal variability of soil moisture was controlled by eight environmental factors at all the measured points at various depths in different seasons on a forested hillslope. The impact of environmental attributes on soil moisture redistribution was pronounced at a depth of 30 cm in all the seasons. The PCR analysis indicated that the effect of environmental attributes on soil moisture variation differed among seasons. In all seasons, at the depth of 10 cm, the variation in soil moisture was attributed to the vegetation, local slope, and soil depth, which indicated that soil moisture strongly depends on infiltration and exfiltration at shallow depths. The seasonal difference in the contribution of environmental factors on soil moisture dynamics was significant at a depth of 30 cm. The main controls of soil moisture in the spring season were soil texture and topography. The effect of local slope and vegetation was increased for the depth of 30 cm during the rainy season due to greater precipitation than in other seasons. The impact of environmental factors determining a variation in soil moisture was insignificant for all seasons at depths deeper than 60 cm. The content of both clay and sand in the soil was significantly correlated with the spatio-temporal variation in soil moisture across seasons. The transitional pattern of environmental controls during rainfall events in the spring and rainy seasons was determined by various environmental factors that depended on rainfall characteristics. The PDFs of soil moisture showed a transition from Normal to Gumbel distribution during spring. PDF variations from the rainy season were more complicated, but those for autumn season were simpler Gumbel and Weibull distributions. This study revealed the effects of diverse environmental factors and transitional control patterns for the spatial distribution of soil moisture during rainfall events in three consecutive seasons.

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**REFERENCES**


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