Spatial and temporal soil moisture and drought variability in the Upper Colorado River Basin

Chunling Tang\textsuperscript{a}, Thomas C. Piechota\textsuperscript{b,}\textsuperscript{*}

\textsuperscript{a} Department of Geosciences, Idaho State University, Pocatello, ID 83209-8072, USA
\textsuperscript{b} Department of Civil and Environmental Engineering, University of Nevada, Las Vegas, 4505 Maryland Parkway, Box 451087, Las Vegas, NV 89154-1087, USA

\textbf{SUMMARY}

This research investigates the interannual variability of soil moisture as related to large-scale climate variability and also evaluates the spatial and temporal variability of modeled deep layer (40–140 cm) soil moisture in the Upper Colorado River Basin (UCRB). A three layers hydrological model VIC-3L (Variable Infiltration Capacity Model – 3 layers) was used to generate soil moisture in the UCRB over a 50-year period. By using wavelet analysis, deep layer soil moisture was compared to the Palmer Drought Severity Index (PDSI), precipitation, and streamflow to determine whether deep soil moisture is an indicator of climate extremes. Wavelet and coherency analysis for the UCRB indicated a strong relationship between the PDSI, climate variability and the deep soil moisture. The spatial variability of soil moisture during current, normal, and wet years was analyzed by using map analysis. Distinct regions showing higher vulnerability to drought and wet conditions were identified in the spatial analysis. The temporal variation in soil moisture was performed by utilizing map analysis in pre-drought, drought, and post-drought years for four drought events, 1953–1956, 1959–1964, 1974–1977, and 1988–1992. Less than 50% of the basin had dry conditions (soil moisture anomaly below –10 mm) for the pre-drought years. Soil moisture anomalies were lower than –10 mm for more than 50% of the basin in 15 out of 19 drought years. Generally, droughts did not end until the average soil moisture anomalies increased to positive values for two consecutive years.

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\textbf{Introduction}

Droughts are characterized by their severity (average water deficiency), magnitude (cumulative water deficiency) and duration. Definitions vary for the different types of drought: agricultural, hydrologic, meteorological, and socioeconomic (Dracup et al., 1980). Several drought indices have been defined for characterization of drought including the use of soil moisture.

Soil moisture is a significant hydrological variable related to floods and droughts and plays an important role in the process of converting precipitation into runoff and groundwater storage. A soil moisture deficit results in more infiltration and little runoff when followed by precipitation. However, high soil moisture results in overland runoff and possible flooding during intense precipitation. In addition, high soil moisture promotes vegetation growth in the summer and this leads to high evapotranspiration. Therefore, soil moisture controls the interaction of the land with the atmosphere.

The influence of soil moisture on climate variability has received attention in recent years. Higher soil moisture may result in higher evaporation and precipitation, and an accurate soil moisture representation can enhance precipitation predictability (Koster et al., 2000). Soil moisture information also has potential to improve seasonal precipitation prediction (Dirmeyer and Brubaker, 1999). Timbal and McAvaney (2001) suggested that a high interannual variability of soil moisture could potentially play a role in affecting Australian seasonal climate forecasts, and Reichle and Koster (2003) found that soil moisture could be important for seasonal prediction of mid-latitude summer precipitation. Huang et al. (1996) identified that precipitation influenced soil moisture anomalies and the soil moisture had greater persistence during periods of low precipitation. Soil moisture has been noted as an indicator of agricultural potential and available water storage, which reflected recent precipitation and antecedent conditions (Keyantash and Dracup, 2002). Trenberth and Branstator (1992) stated that there are three main contributors to drought: land and sea surface temperature, atmospheric circulation, and soil moisture. Changes of each of these parameters were amplified to produce climate extremes such as flood or drought.

Recent research has focused on the relationship between soil moisture and the Palmer Drought Severity Index (PDSI) (Palmer, 1965). This index is a widely accepted drought indicator that has been used in many studies to assess drought severity.
Soil moisture interacts with the atmosphere through surface energy and water balances. Poveda and Mesa (1997) analyzed soil moisture, ENSO (El Niño–Southern Oscillation), and precipitation in Colombia and demonstrated that soil moisture accounted for part of the precipitation reduction in tropical South America through reduction in evapotranspiration and feedback mechanisms. Several studies have looked at the temporal variability of soil moisture. Hu et al. (1997) examined the temporal function of soil moisture, and suggested that it was related to infiltration, cloud coverage, precipitation, and drainage. In evaluating water resources in small catchments, soil moisture varied spatially due to water routing processes, vegetation, and soil types (Hu et al., 1997). To fully understand the changing dominance of soil moisture in different regions, its spatial characteristics need to be considered along with the temporal characteristics. The study presented seeks to evaluate both the spatial and temporal aspects of soil moisture in extreme climate conditions.

There are three main objectives in this study. The first objective is to generate large-scale, long-term, high-resolution soil moisture based on model calibration and model verification in the UCRB. Modeling soil moisture is important because the lack of consistent high-resolution, large-scale, long-term modeling soil moisture has prevented certain research, such as the linkages of the soil moisture with climate variability. The second objective is to examine soil moisture as a drought indicator with the main contribution due to water routing processes, vegetation, and soil types (Hu et al., 1997). To fully understand the changing dominance of soil moisture in different regions, its spatial characteristics need to be considered along with the temporal characteristics. The study presented seeks to evaluate both the spatial and temporal aspects of soil moisture in extreme climate conditions.

The VIC-3L model is a macro-scale water and energy balance model, based on the Xinnan Jiang Model (Zhao et al., 1980). The VIC-3L model description follows.

The VIC-3L model was used to simulate soil moisture at a daily time step with a 1/8° spatial resolution for the period 1950–2000 in the UCRB. Then, the relationships between soil moisture and climate variability was evaluated by wavelet method. The spatial variability of soil moisture during drought, normal, and wet years was investigated by using map analysis method. Finally, the role of the temporal variability of soil moisture during the initiation, persistence, and termination of drought was evaluated by map analysis. A detailed description of these methods follows.

Development of soil moisture dataset

The VIC-3L model is a macro-scale water and energy balance model, based on the Xinnan Jiang Model (Zhao et al., 1980). The distinguishing features of the VIC-3L model include the sub grid variability in soil moisture, land surface vegetation, precipitation, and topography in use of the elevation band. The VIC-3L model
had been successfully applied over many large river basins with reasonable results (Abdulla et al., 1996). The VIC-3L model is based on the water balance equation:

$$D_S = p - ET - R - D$$

where $D_S$ is the rate of the change of storage, $p$ the precipitation, $ET$ the evapotranspiration, $R$ the surface runoff, and $D$ is the subsurface runoff.

The VIC-3L model consists of three soil layers, 10 cm for layer 1, 30 cm for layer 2, and 100 cm for layer 3. Surface runoff is generated in the upper two layers by a variable infiltration curve, and baseflow is produced in the bottom layer (Todini, 1996). The VIC-3L model allows different types of vegetation and land cover. The surface land cover types are described by $n = 1, 2, 3, \ldots, N, N+1$ ($N$ represents different types of vegetation, and $N+1$ represents bare soil). Land cover types are characterized by their Leaf Area Index (LAI), canopy resistance, root fraction depth, and soil properties (Liang et al., 1994).

The VIC-3L model typically runs at spatial resolutions varying from $1/8^\circ$ to $2^\circ$, temporal resolutions from monthly to daily time.

Fig. 1. The UCRB with five streamflow stations from the USGS and five climate divisions from the NOAA.
steps, and is forced by meteorological data, soil data, and vegetation data. The model is coupled to a routing model, which generates streamflow and transports grid cell surface runoff and baseflow produced by the VIC-3L model to the outlet of that grid cell, and then into the river system (Wood et al., 1997). A more thorough description of the model is given in Liang et al. (1994) and Lohmann et al. (1998).

For soil moisture, Nijssen et al. (2001) reported a good comparison between the simulated soil moisture by the VIC-3L and the observed soil moisture in central Illinois and in central Eurasia. Another study by Maurer et al. (2001) demonstrated that the VIC-3L modeled soil moisture had a higher persistence than the NCEP (National Center for Environmental Prediction) reanalysis data for the entire Mississippi River Basins. Stephen et al. (2008) compared the VIC-3L modeled soil moisture with observed soil moisture in the Lower Colorado River Basin and show that the two soil moisture datasets match well.

The VIC-3L model calibration

Observed streamflow. The model calibration was performed between observed streamflow and simulated streamflow. Streamflow stations were identified from the National Water Information System Web (NWISWeb) Data retrieval (http://waterdata.usgs.gov/nwis/) of the United States Geological Survey (USGS) (Slack et al., 1993) and monthly average flow rate were retrieved. There are several reasons for calibration of streamflow rather than soil moisture. First, long-term observed soil moisture is not available in the UCRB. Second, the output of the VIC-3L model are the main input sets of the routing model, so calibration of the streamflow which is the output of the routing model indirectly calibrates the VIC-3L model. Third, the soil moisture parameter is one of the most sensitive parameters in the calibration of the streamflow. Streamflow is a spatially integrated response of hydrologic processes within a basin, which is important for assessing land surface schemes at large spatial scales. The monthly streamflow over a 50-year period (1950–2000) for five stations in the UCRB (Fig. 1) (Fall Creek, Piney River, Cisco, Green River, and Lee’s Ferry) were used for calibration.

Selection of sensitive parameters. The calibration of the VIC-3L model is usually performed by adjusting five parameters (Wood et al., 1997): (a) the maximum baseflow that can occur from the third soil layer (in mm/day) ($D_{smax}$); (b) the fraction of $D_{smax}$ where non-linear (rapidly increasing) baseflow begins ($D_s$); (c) the fraction of the maximum soil moisture (of the lowest soil layer) where non-linear baseflow occurs ($W_{smax}$); (d) the infiltration parameter ($b_m$); and (e) the depth of the second soil layer ($d_2$). Since the maximum velocity of baseflow ($D_{smax}$) depends on hydraulic conductivity, which can be estimated using the saturated hydraulic conductivity multiplied by the slope of the grid, the fraction of maximum soil moisture content of the third layer ($W_{smax}$) is analogous to $D_s$ (Liang et al., 1994; Wood et al., 1997). These three
parameters can be derived from soil textural information, so, the parameters were used with minor adjustment during the calibration in this research. Consequently, the infiltration parameter \( b_{nf} \), and the thickness of the second soil layer \( d_2 \) were treated as the primary calibration parameters (Wood et al., 1997; Su et al., 2005). These two parameters were chosen as the primary calibration parameters for several reasons. First, sensitivity analysis showed that \( b_{nf} \) and \( d_2 \) were the most sensitive calibration parameters. Second, a change in the thickness of the second layer affects not only the hydraulic conductivity, but also the maximum storage available in the second layer and the water available for transpiration. The plant roots can draw water only from the top two soil layers and the baseflow was generated only from the third layer in the VIC-3L model. As a result, the flux of water from the second layer into the third layer determines how much baseflow will occur.

Of the total 50-year record, a 30-year period (1971–2000) was utilized for the calibration process, and a 20-year data (1950–1970) was used for validation. Model validation applied the VIC-3L model without changing the calibration parameters \( b_{nf}, d_2 \) values obtained from calibration. The root mean squared error (RMSE) and linear correlation coefficient \( (r) \) were the two calibration criteria.

Model verification

The model verification was performed by comparing soil moisture calculated from the VIC-3L model with that from the Distributed Modeling Intercomparison Project (DMIP) of the CPC (Climate Prediction Center) for five Climate Divisions (33, 298, 299, 300, and 337) (Fig. 1) in the UCRB. Soil moisture produced by the CPC has been widely used in climate studies in recent years. The verification is difficult to perform because different soil layer depths and different soil moisture reservoir sizes were utilized in the CPC and the VIC-3L model. The CPC defined the maximum soil moisture capacity as 760 mm (Refsgaard, 1997) and the soil was set to only one layer with 1.6 m depth. In contrast, the maximum soil moisture in the VIC-3L model was equal to the porosity of the soil, and soil moisture storage expressed as a fraction of field capacity. Soil was separated into three layers with a total 1.4 m depth in the VIC-3L model rather than 1.6 m in the CPC. Because of these differences, the verification was carried out by a comparison of the soil moisture anomaly patterns rather than the absolute storage values. The verification relied upon the correlation between the two datasets:

\[
\text{r}_{jk} = \frac{\text{COV}_{jk}}{S_j S_k}
\]

Fig. 3. Monthly observed and simulated streamflow for: (a) Fall Creek station, (b) Piney River station, (c) Green River station, (d) Cisco station, and (e) Lee’s Ferry station.
where $S_j$ and $S_k$ are the standard deviations of variable $j$ and $k$, respectively, and $COV_{jk}$ is the correlation between $j$ and $k$.

To calculate the covariance between the two soil moisture datasets, the corrected sum of products $(SP)$ which shows the sum of squares of variables is defined by:

$$ SP_{jk} = \sum_{i=1}^{n} (X_{ij} - \bar{X}_j)(Y_{ik} - \bar{Y}_k) $$

(3)

where $j$ is the soil moisture from the VIC-3L model, $k$ is the soil moisture from the CPC, $X_{ij}$ is the $i$th measurement of variable $j$, and $Y_{ik}$ is the $i$th measurement of variable $k$. $\bar{X}_j$ is the mean of variable $j$, and $\bar{Y}_k$ is the mean of variable $k$.

The covariance was then calculated based on $SP$:

$$ COV_{jk} = \frac{SP_{jk}}{n-1} = \frac{n\sum_{i=1}^{n} X_{ij}Y_{ik} - \sum_{i=1}^{n} X_{ij}\sum_{i=1}^{n} Y_{ik}}{n(n-1)} $$

(4)

Comparison of time series

The next step was to compare soil moisture with other drought indicators by using wavelet analysis. Methods used to analyze signals for time variation are standard techniques such as Fourier and wavelet analysis. The main problem with the Fourier transform is no time localization of the frequencies are present in the signal (Torrence and Webster, 1999). Wavelet analysis attempts to solve this problem by decomposing a time series into time/frequency space simultaneously. Information on both the amplitude of any periodic signals within the series and how this amplitude varies with time is provided by wavelet analysis.

The continuous wavelets transform $W_n$ of a discrete sequence of observations $x_n$ is defined as the convolution of $x_n$ with a scale $s$ and wavelet $\psi(x)$:

$$ W_n^x(s) = \sum_{n'} x_{n'} \psi \left( \frac{n' - n}{s} \right) $$

(5)

where $n$ is the localized time index, $s$ is the wavelet scale, $\delta t$ is the sampling period, $N$ is the number of points in the time series, and the asterisk indicates the complex conjugate. The wavelet transforms $W_n(s)$, at time index $n$, scale $s$ and with a constant time interval were developed (Torrence and Webster, 1999) for all the given time series (soil moisture of layer 1, layer 2 and layer 3, PDSI, precipitation, and streamflow).

The similarity between the different time series was evaluated by using wavelet coherency, which was used to identify frequency bands and time intervals where two time series were related (Torrence and Webster, 1999). The wavelet coherency $R_n$ is defined as:

$$ R_n^2(s) = \frac{|(s^{-1}W_{nX}(s))|^2}{(s^{-1}|W_{nX}(s)|^2)(s^{-1}|W_{nY}(s)|^2)} $$

(6)

where $(\quad)$ indicates smoothing in both time and scale, $W_n^X(s)$ and $W_n^Y(s)$ are the wavelet transforms of two time series $X$ and $Y$. $W_{nX}(s)$ is the cross-wavelet spectrum of two time series $X$ and $Y$ which is defined as:

$$ W_{nX}^{XY}(s) = \sum_{n'} X_{n'} W_n^{XY}(s) $$

(7)

Fig. 4. Comparison of soil moisture anomaly simulated from the VIC-3L model and from the CPC.
where \((*)\) means the complex conjugate. The intent of the wavelet coherency analysis is to determine how well soil moisture represents hydrological drought in the UCRB.

**Spatial variability of soil moisture during droughts**

To evaluate the spatial variability of soil moisture, map analysis was performed on the 50-year period which was divided into drought, normal, and wet years. In this study, the PDSI value of \(-1\) was selected as the threshold. Drought was defined as the consecutive years during which the PDSI variable was continuously below \(-1\). The normal years were defined as the years with the PDSI values between \(-1\) and \(1\). The wet years were identified as the PDSI greater than \(1\). This resulted in 19 drought, 14 normal, and 17 wet years over the 50-year records which is consistent with the study of Timilsena et al. (2006). Secondly, gridded yearly average soil moisture and soil moisture anomaly for the drought, normal, and wet years were calculated. Finally, maps displaying the temporal and spatial variability of soil moisture were developed.

**Temporal variability of soil moisture during droughts**

As discussed above, there are 19 drought years and four drought events over a 50-year record. In general, two years before and after the drought were chosen for the pre-drought and post-drought analysis, so the soil moisture anomaly response before and after a drought event could be evaluated. A total 19 drought years, 8 pre-drought years, and 8 post-drought years were evaluated in the map analysis. Secondly, the areas were defined as in dry, normal, and wet conditions based on soil moisture anomalies, and used the following classification scheme: dry condition (soil moisture anomaly below \(-10\) mm), normal condition (soil moisture anomaly between \(-10\) mm and \(10\) mm), and wet condition (soil moisture anomaly greater than \(10\) mm). The percentages of the basin in different conditions were calculated for pre-drought, drought, and post-drought years.

**Results**

**Calibration results**

The results of the calibration are presented in Fig. 3, which compares the monthly modeled streamflow with the observed streamflow at Fall Creek, Piney River, Green River, Cisco, and Lee’s Ferry stations from 1950 to 1960. The maximum error between these data sets is less than 5% for the UCRB. The monthly hydrographs closely match the observations, which indicates very low flows during November–April and high flows during May–October for the five stations. The model simulations capture the time of the peak flows, but overestimate the flows in 1950, which could possibly be due to the initialization of the model.

**Soil moisture verification**

The CPC soil moisture datasets used for verification were generated from observed precipitation and temperature (Refsgaard, 1997). Model verification was carried out for each Climate Division (Fig. 1) and the entire UCRB. Only the verification results of the whole UCRB for period 1950–2000 were represented in Fig. 4. The comparisons of the two soil moisture datasets demonstrated similar results for the five Climate Divisions as those for the whole UCRB in Fig. 4a. A comparison revealed that the seasonal cycles in soil moisture were well captured and the two models matched reasonably well. The soil moisture anomaly in the CPC tended to be higher than that of the VIC-3L model for the period 1967–1972 and lower for the period 1977–1981. The VIC-3L model predicts
soil moisture values 1.5% lower than the data from the CPC. Fig. 4b presents the scatter and correlation of the monthly soil moisture anomalies from the CPC and the VIC-3L model. The scatter plot illustrates a relatively high correlation of 0.82 between the CPC and the VIC-3L soil moisture anomalies. The correlations for the five Climate Divisions (not shown) were 0.80, 0.78, 0.81, 0.83, and 0.83, respectively.

### Soil moisture in the UCRB

The VIC-3L model soil moisture is presented in Fig. 5. The daily time scale modeled soil moisture of layer 1, layer 2, and layer 3 was averaged to monthly values and displayed in Fig. 5a. The soil moisture of layer 1 shows a higher frequency of variation and this may be attributed to the structure of the VIC-3L model where layer 1 soil responds to precipitation immediately and has a smaller infiltration capacity, in comparison with the layer 2 and layer 3 soil. The highest amplitudes variation with lowest frequencies occurred in the layer 3. This suggests that extreme climate occurs at longer time scales and the soil storage is higher in the deeper soil layer. Soil moisture data varied from 12.9 mm to 23.4 mm for the layer 1, 37.2 mm to 70.5 mm for the layer 2, and 106.0 mm to 216.7 mm for the layer 3. Soil moisture values for the layer 2 and layer 3 show some drastic reduction for certain drought years, for example, 1964–1966 and in the late 1970s. The maximum soil moisture deficit in layer 3 occurred during the late 1990s, which provides insight to drought characterization, coincided with the current drought studied by Piechota et al. (2004).

The variation of the yearly averaged soil moisture was studied for the five Climate Divisions, however, only the results of three Climate Divisions (298, 300, and 337) were presented in Fig. 5b. High soil moisture occurred from 1982 to 1983; this may be due to wet conditions derived by the El Niño event. All Climate Divisions show a decrease in soil moisture for several periods, for instance, the year 1956 and 1963, the late 1970s and the 1980s, and the late 1990s.

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**Fig. 6.** Wavelet power spectrum of the six time series: (a) soil moisture of layer 1, (b) soil moisture of layer 2, (c) soil moisture of layer 3, (d) the PDSI, (e) streamflow, and (f) precipitation. The scale of the power spectrum is a log2 representation of the power spectrum value.
Comparison of soil moisture and drought indicators

Wavelet analysis was conducted on six time series: soil moisture of layer 1, soil moisture of layer 2, soil moisture of layer 3, streamflow at Lee’s Ferry, precipitation, and the PDSI in the UCRB. The wavelet power spectrum for these six time series are presented in Fig. 6, which shows the temporal fluctuation of the variables over the entire 50-year period. For soil moisture of layer 1, layer 2, and layer 3 (Fig. 6a–c), the power is widely distributed, with peaks in the 1-year, 4–8 year and the 8–16 year bands. The 1-year frequency band in the soil moisture of layer 1 coincides with the annual cycle precipitation (Fig. 6f). The wavelet results of the PDSI display a dominant feature of a high spectrum for the period of 4–8 year, representing the periodicity of 4–8 years frequency cycle coincides with El Niño events. Variance changes similar to the soil moisture are found in the PDSI (Fig. 6d), and streamflow (Fig. 6e) over the 4–8 year and the 8–16 year bands which means that the soil moisture is closely linked to the PDSI and streamflow. Over the entire range of frequencies and time periods, the most similar wavelet power spectrums are for soil moisture of layer 3 and the PDSI. There is a significant covariance between them in the 4–8 year band. This is expected since the PDSI is partially computed based on soil moisture values. Furthermore, Lakshmi et al. (2004) found similar results for the Mississippi River Basin.

To further investigate the similarities of the six time series, wavelet coherency was performed between all of the time series. Fig. 7 depicts the wavelet coherency of soil moisture of layer 1 with the PDSI (Fig. 7a), soil moisture of layer 2 with the PDSI (Fig. 7b), and soil moisture of layer 3 with the PDSI (Fig. 7c). The wavelet coherency between soil moisture of layer 1 and the PDSI is greater than 0.8 for most times in the 1–2 year band, and it exceeds 0.85 during the intervals from 1965 to 1980. The coherency between soil moisture of layer 2 and the PDSI demonstrates high values for in the 2–4 year band and in the 4–8 year band. The soil moisture of layer 3 and the PDSI identify significant coherency in the 4–8 year band and the 8–16 year band, with relatively low coherency outside of these periods, which indicates that the soil moisture is strongly correlated to the PDSI at the similar frequency patterns as the El Niño (every 3–7 years). The changes in the PDSI and soil moisture of layer 3 appear with high coherency from 1955 to 1985.

Table 1 summarizes the coherency between the six time series of 95% significant level. Similar to the comparisons made in Fig. 7, the coherence between the soil moisture of layer 1 and the soil moisture of layer 2 is 0.9. This represents the high amount of interflow between these two soil layers. The PDSI and the soil moisture of layer 3 are coherent at 0.88. This suggests that the soil moisture of layer 3 could be utilized as an indicator of extreme climate conditions (e.g., droughts and floods). Lastly, precipitation and the soil moisture of layer 3 have a moderate coherency (0.85) that further highlights the usefulness of the soil moisture of layer 3 as an indicator of hydroclimatic conditions. The coherency between precipitation and the soil moisture of layer 1, precipitation and the soil moisture of layer 2 are 0.85 and 0.87, respectively. This may be due to the quick response of the layer 1 and layer 2 soils to the precipitation.

Spatial variability of soil moisture

Fig. 8 represents soil moisture maps, displaying the 50-year average gridded soil moisture (Fig. 8a), the average soil moisture anomaly for the drought years (Fig. 8b), the normal years (Fig. 8c), and the wet years (Fig. 8d). There were six regions with low soil moisture in Fig. 8a, four of them, regions 1–4, were located in the western-central UCRB. These regions are mostly located in the Colorado plateau with barren or sparse vegetation (Fig. 2b). Region 1 had the lowest average soil moisture, where the average soil moisture was below 20 mm. Another two regions, regions 5 and 6, with lower soil moisture, were identified in the lower portion of the basin, with barren or sparse vegetation (Fig. 2b) and sandy soils (Fig. 2c). The soil moisture in Climate Division 33 was higher than that of other Divisions. The deep loam clay soil (Fig. 2c) is the major
soil type and the needle leaf forest (Fig. 2b) comprises most part of this Division. Three regions, regions 7, 8, and 9, with high soil moisture stand out. Region 7 was in the upper corner of the basin, which is affected by snow melt. Regions 8 and 9, along the east of the basin, are also affected by snow melt and have more vegetation, which leads to deep, dark, and rich soils.

Three maps (Fig. 8b–d) shows the spatial patterns of soil moisture anomalies for different time periods: drought, normal, and wet years. When taken together, the three maps display a spatial picture of the changes of soil moisture anomalies for three different periods. Two regions, regions 1 and 2 (Fig. 8b), were identified with lower soil moisture anomaly over the drought years. These regions are mostly covered by shrub land, and some areas are comprised of barren or sparse vegetation. The soil moisture anomaly during the drought years ranged from \(-40.00\) mm to 0 mm with the averaged value of \(-12.7\) mm.

The soil moisture anomaly displays a lower variation with lower amplitudes in the normal years (Fig. 8c), in which the average soil moisture anomaly was 0.7 mm. Two distinct regions (Fig. 8d) were identified as being sensitive to wet conditions. These two regions have a similar spatial concentration in comparison with the significant regions in the drought map (Fig. 8b). The response pattern of vegetation to drought and wet conditions may contribute to the sensitivity of the soil moisture anomaly to the drought and wet conditions.

### Temporal variability of soil moisture

The soil moisture anomalies in three periods: pre-drought, drought, and post-drought years for two drought periods were identified and displayed in Figs. 9 and 10. Yearly average soil moisture anomalies for all four drought periods are showed in Table 2. The percentages of regions in dry, normal, and wet conditions for the pre-drought, drought, post-drought years are also displayed in Table 2.

For the pre-drought year of 1951, over 66% of the UCRB experienced dry conditions (soil moisture anomaly below \(-10\) mm) (See Fig. 9). However, in 1952, only 16% of the basin had dry conditions. Sheffield et al. (2004) noted that the surface was dry but the deeper layer soil was wet in 1952 due to long-term variation in climate. During the drought period (1953–1956), over 50% of the basin had negative soil moisture anomalies. Lower soil moisture anoma-
aly might have played a major role in accelerating the widespread of the drought. The average soil moisture anomaly reached a historical low value of \(-26.13\) mm, and 83% of the basin had dry conditions. The sudden increase of the soil moisture anomalies and decrease of dry regions in 1957 were due to the spring rain in 1957 (Sheffield et al., 2004). Less than 50% of the basin had negative soil moisture anomalies in two post-drought years (1957 and 1958). Average soil moisture anomalies increased to positive values (Table 2) in 1957 and 1958, which signaled the end of the four year drought.

soil moisture anomaly (mm)

\[
\begin{array}{cccccccc}
-140 & -40 & -39 & -20 & -19 & -10 & -9 & 0 & 10 & 20 & 40 & 140 \\
\end{array}
\]

Fig. 9. Soil moisture anomaly with the percentage of dry regions for the pre-drought, drought, and post-drought periods of the year 1951–1958.
The drought of the years from 1988 to 1992 (Fig. 10c–g) cost more than $30 billion losses over the United States and has been considered to be one of the worst disasters in the US (Trenberth and Branstator, 1992). The main factors in the development of this drought were the combination of the sea surface temperature, associated with the La Niña and the feedback of soil moisture with precipitation (Trenberth and Branstator, 1992). However, more than 50% of the basin had dry conditions for three out of the five drought years. The average soil moisture anomalies were negative for the five drought years. The soil moisture began to increase with wet conditions across the southern to the central

Fig. 10. Soil moisture anomaly with the percentage of dry regions for the pre-drought, drought, and post-drought periods of the year 1986–1994.
ability and the correlation between them was relatively high.

During the verification test, it was noted that from the CPC center. The model verification was performed by comparing simulated soil moisture from the VIC-3L model with observed streamflow, which never exceeded 5% during the validation period. The model was able to produce the streamflow and soil moisture quite well.

The simulated soil moisture was related to the PDSI, streamflow, and precipitation by utilizing wavelet and coherency analysis in the UCRB. The wavelet coherence analysis presented the relationships between six time series (soil moisture of layer 1, layer 2, and layer 3, the PDSI, streamflow, and precipitation). The soil moisture of layer 3 showed high correlation with the PDSI (0.88) and this suggests that soil moisture may be a good drought indicator or a central variable for characterizing the hydrologic status for the UCRB.

Then the study identified the spatial and temporal variability of soil moisture in response to drought events using 50-year soil moisture data (1950–2000) in the UCRB. In the spatial analysis, regions identified with more sensitivity to wet and dry conditions were the western-central parts of the basin. In general, regions with lower soil moisture were associated with the barren or sparse vegetation and sandy soil. The regions with high soil moisture are consistent with high vegetation density (needle leaf forest).

The temporal soil moisture conditions were evaluated by examining soil moisture in three different periods: pre-drought, drought, and post-drought of four drought events. The results from the 35 maps created for the temporal analysis demonstrated that the average soil moisture anomalies were negative for the drought periods. Also, the droughts did not end until two consecutive years of positive soil moisture anomalies. For pre-drought years, soil moisture anomalies decreased for two drought events (e.g., 1974–1977, and 1988–1992). However, for another drought event (e.g., 1953–1956, and 1959–1964), soil moisture did not have negative anomalies prior to the drought. This may be due to the sequence of the drought impacts identified by Andreadis and Lettenmaier (2006). The sequence begins with meteorological (precipitation) drought and as its duration increases, agricultural (soil moisture) drought, and then hydrological (streamflow) drought follow. For drought periods, more than 50% of the basin had dry conditions for 15 out of 19 drought years. For post-drought periods, greater than 50% of the basin had normal and wet conditions, and the average soil moisture anomalies were positive for all the 10 post-drought years, which indicate that only one year with positive average soil moisture anomaly was not enough to end a drought.

### Table 2

Yearly Average soil moisture anomalies and percentage of basin had dry, normal, and wet conditions for the pre-drought, drought, and post-drought for four drought events.

<table>
<thead>
<tr>
<th>Catalog</th>
<th>Years</th>
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### Conclusion

This research presented a simulation of soil moisture by the VIC-3L model at a 1/8° resolution and a daily time step over a 50-year period in the UCRB. This simulation offered a spatial and temporally long-period, high-resolution soil moisture dataset for the UCRB. The observed and simulated soil moisture values were in reasonably good agreement and differences between simulated and observed streamflow never exceeded 5% during the validation period. The model verification was performed by comparing simulated soil moisture from the VIC-3L model with that from the CPC center. During the verification test, it was noteworthy that the two soil moisture datasets showed similar variability and the correlation between them was relatively high (0.82). The 50-year simulations over the UCRB indicated that the VIC-3L model was able to produce the streamflow and soil moisture quite well.

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