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PLANFORM EFFECTS ON SIMULATED HILLSLOPE SOIL MOISTURE IN AN UPLAND FORESTED WATERSHED

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ABSTRACT

The effect of planform on hillslope soil moisture distribution was investigated using a terrain-fitted TAPES-C watershed hydrology model (IHDM4) at the Coweeta Hydrologic Laboratory. Soil moisture on hillslopes of contrasting planforms (convergent vs divergent from ridge stream) was simulated using a 14 year series of climate data. Mean soil moisture in 3 layers (0-25 cm, 100 cm, 100 cm-bedrock) on each hillslope varied with PPT-PET (precipitation minus evapotranspiration). During drought, soil moisture gradients along hillslopes increased with no significant control by planform. During recharge, however, planform affected significant changes in soil moisture gradients between hillslopes of different planform due to persistent saturation near the outlet of the convergent hillslope.

INTRODUCTION

Distribution of soil moisture on hillslopes in watersheds plays an important role in determining vegetation distribution, slope stability, runoff and erosion. Hydrologists have studied patterns of hillslope moisture in the southern Appalachian mountains for decades. For these humid, deep-soiled watersheds, several general conclusions have emerged: (a) cove and ridge sites have comparable annual soil moisture content, and both tend to be wetter than midslope sites; (b) variation in soil moisture
is less in cove sites than upper slope sites; (c) va
in soil moisture decreases with depth [4]. Physio
control on soil moisture has been observed to vary
topographic features (i.e., local slope, con tributing area) and soil properties (i.e., t
class, horizon depths), depending on rainfall [5].

Hillslope shape, from planview, has been observed
an important control on hillslope runoff. Converging
headwater) hillslopes, when contrasted with diverging
(sideslope) hillslopes, tend to maintain moisture con
closer to saturation near the outflow [6-8]. Con
areas have been observed to yield earlier and high
runoff flow rates per unit area [7].

Our objective was to simulate the effect of hi
planform on soil moisture distribution in an upland f
watershed at Coweeta. We used a terrain-fitted hi
hydrology model to contrast soil moisture distri
along two adjacent hillslopes that were oppos
planform. We performed simulations for 14 years of
climate data that spanned several seasonal drougl
high-rainfall periods. We correlated series of si
soil moisture content and gradients with ser
atmospheric moisture conditions to determine differe
the way these hillslope planes responded.

METHODS

Study Site

The site was Watershed 2 (WS2), a 12.3 ha wate:sh
dsecond-growth oak-hickory vegetation, southern aspec
slope of 60%, at the Coweeta Hydrologic Laborator;
primary soil series for lower elevations of WS2 are c
of sandy loam to clay loam [5]. Hillslopes were det
from analyses of WS2 using a terrain analysis model,
[9-11]. Two adjacent hillslopes having con planforms were selected: a convergent plane wi
changing from 9.9 m stream-side to as wide as 71.4 m <
upper slope; and a divergent plane with width changing
54.8 m stream-side to 3.2 m on the divide (planes #
#12 in [11]). The divergent hillslope was instrumented
time domain reflectometry (TDR) along an 85 m transect
ridge to stream. TDR plots were established at
intervals to 40 m from the stream, then at 10 m intervi
the ridge. Each plot had 3 replicates through each
depths (30 cm, 90 cm). Soil moisture was measured alo
transect from the end of a severe, autumn drought (Nov
1991) through winter precipitation recharge (Feb
1992) [5].

Simulation Model
A terrain-based hillslope hydrology model was dev<
from existing models [10-12]. The model consisted
canopy interception component [13] and a 2-D finite e'.
hillslope hydrology component [14] having hillslope %
determined using TAPES-C [9]. Parameterization of the
was performed based on information from previous stud)
Coweeta [12]. Calibration of the model was conducted
streamflow for three storms covering a large range of
types and antecedent conditions. Final parameters us
the simulations are given in the Appendix. Validatic
performed for measured soil moisture conditions of
divergent hillslope over the period of drought and rec
as shown in the Appendix. Simulations were conducted hourly timestep for both hillslope planes for a 14
period. .

Climate Data
Data were taken from two climate stations (CS01, and one rain gauge (RG20) for the study period (1975:
All instruments were located within 1 km of WS2. Wit
exception of rainfall, daily to hourly transformations
required for much of the data.[12]. From 1986-1991, 1
measured solar radiation and windspeed were available. Translation of direct solar radiation measured by horizontal solarimeter at CS01 to the slope and aspect of V performed following [15].

**Approach**

The two hillslopes, with the same soil and vegetation parameters (see Appendix), were simulated for a 14 month period (May, 1975, to Dec, 1989) using the climate at an hourly timestep. Planform differences distinguished the two hillslopes. The first 8 months were used as an initialization period and discarded. Soil moisture content was aggregated for three layers on each hillslope: 0-25 cm (top); 25-100 cm (middle); 100-200 cm (bottom). Moisture gradients were computed as linear regression slopes, where the independent variable was normalized plane distance along the hillslope, varying from 0 to 1. The dependent variable was fractional moisture content, varying from approximately 0.05 to 0.4. Moisture gradient could then vary from 0% (no change along hillslope) to ±40% (maximum change along hillslope).

Atmospheric moisture represented by PPT-PET, where precipitation and PET is potential evapotranspiration (Penman-Monteith) summed over a 24 hour period, was used to characterize input of moisture to the hillslopes. A filter was fitted to the input series of PPT-PET on a timestep [16]. This filter was used to pre-whiten the series and the two output series (daily mean soil moisture content, daily soil moisture gradient) before computing cross-correlation functions.

**RESULTS AND DISCUSSION**

**Climate Characterization**

Running means of the 14 year PPT-PET daily series computed at monthly and seasonal (4 month) time periods where PCs 310
evapotranspiration exceeded precipitation, i.e. di
occurrence. At the **timescale** of a month, PET>PPT occ
37 times in 14 years; at the timescale of 4 months, PI
occurred 15 times in 14 **years**. The greatest sec
droughts (at least six months where PET>PPT) occurred <
series of PPT-PET were best fit by an **AR(1)** filter,
subtracting out the series mean:

\[ a_t = (PPT-PET)_t - 0.184 \times (PPT-PET)_{t-1}. \]

No differencing was required to achieve **stationarity**.

**Hillslope Responses**

Cross-correlation between daily PPT-PET and mean
moisture content for a given soil layer showed a simili
on both hillslopes. For 0-25 cm and 25-100 cm l
significant cross-correlations (where 2 std. dev. frot
was computed by \(2 \times n^{-1/2}\), with \(n = 5114\) days \[16\]) per,
up to 3 weeks. The most **significantly correlated hil
moisture response for top and middle layers was < 1 da
The bottom layer on each hillslope, in contrast,
significant cross-correlations between PPT-PET and
moisture content for lags up to 3 **months**. Com
hillslopes, the shape of the cross-correlation functi
very similar. These results indicate that hil
**planform difference** had no **effect** on the relation b
atmospheric moisture and **simulated** mean soil mo
response for any layer on the hillslopes.

Cross-correlation between daily PPT-PET and soil mo
gradient, however, showed different **responses** com
divergent and convergent hillslopes. For, the div
hillslope, a **positive** correlation as resulted for 0-
and 25-100 cm layers, with significant correl
persisting over a month. This indicates that as PET
ridge soils successively became drier than near-stream
in the upper 100 cm. Lower layer (>100 cm) soil showe
marginal correlation with atmospheric moisture. Fr
convergent hillslope, however, a positive cross-corn only occurred in the 0-25 cm layer, and was only short
(lag < 7 days). The dominant response in all con' hil
slope soil layers was a negative cross-correlation persisting up to 2 months, with peak at about 3-4 weeks. When PPT > PET, near-stream soils became significant saturated than when PPT < PET. Relative increases in stream soil moisture content under wet atmos conditions caused higher differences between ridge and stream soil moisture, hence the higher gradient.

Observation of hillslope soil moisture for the slope, at a seasonal timeframe of recharge after drought, illustrates differing responses for opposite planforms (Fig. 1). The period spanned drought (1978) through recharge (March 1979), where the four running mean for PPT-PET changed from less than -5 more than +12 cm. For the divergent hillslope, difference in soil moisture content from stream to ridge was greater during drought. After recharge, soil moisture was uniform along the hillslope (Fig. 1). For the conv hillslope during drought, difference in soil moisture content was comparable to that found on the divergent hillslope. After recharge, however, a near-stream saturated condition occurred for the convergent hillslope (Fig. 1). This saturated condition persisted due to the planform of the convergent hillslope.

Persistent overland flow occurred from the near-area of the convergent hillslope. This simulated results not surprising [6-7]. Intermittent streams emerged in convergent areas during periods of high rainfall have been observed in upland watersheds at Coweeta. Simulated results suggest that planform alone has a minor effect on soil moisture distribution as drought progresses during drought. During high rainfall seasons however, planform can exert significant control over hillslope soil moisture distribution.

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Figure 1. Mean monthly soil moisture at each of three layers along the two hillslopes at the end of a severe drought (Oct78) and after winter recharge (Mar79) for WS2 at Coweet...
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REFERENCES


APPENDIX

I. Calibrated model (IHDM4) parameters.

<table>
<thead>
<tr>
<th>Canopy characteristics</th>
<th>Summer</th>
<th>Transition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roughness Length (z₀)</td>
<td>.02</td>
<td>.035</td>
</tr>
<tr>
<td>Zero plane displ (d)</td>
<td>.83</td>
<td>.665</td>
</tr>
<tr>
<td>Albedo</td>
<td>.22</td>
<td>.19</td>
</tr>
<tr>
<td>Throughfall fract (p)</td>
<td>.47</td>
<td>.645</td>
</tr>
<tr>
<td>Canopy height (h) [m]</td>
<td>19</td>
<td>19.</td>
</tr>
<tr>
<td>Interception storage (S) [cm]</td>
<td>.2</td>
<td>.15</td>
</tr>
<tr>
<td>Drainage parameter (K) [cm/h]</td>
<td>3.3e-4</td>
<td>7.4e-4</td>
</tr>
<tr>
<td>Drainage parameter (b) [cm/h]</td>
<td>22.2</td>
<td>22.2</td>
</tr>
</tbody>
</table>

Conductivity by soil layer

<table>
<thead>
<tr>
<th>Layer</th>
<th>Depth [cm]</th>
<th>Sat. Kᵥ [cm/h]</th>
<th>Sat. Kᵥ [cm/h]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0-25</td>
<td>.20</td>
<td>4.0</td>
</tr>
<tr>
<td>2</td>
<td>25-50</td>
<td>.05</td>
<td>1.0</td>
</tr>
<tr>
<td>3</td>
<td>50-75</td>
<td>.015</td>
<td>0.3</td>
</tr>
<tr>
<td>4</td>
<td>75-100</td>
<td>.015</td>
<td>0.3</td>
</tr>
<tr>
<td>5</td>
<td>100-150*</td>
<td>.003</td>
<td>0.06</td>
</tr>
<tr>
<td>6</td>
<td>150-200*</td>
<td>.003</td>
<td>0.06</td>
</tr>
<tr>
<td>7</td>
<td>200-250*</td>
<td>.003</td>
<td>0.06</td>
</tr>
<tr>
<td>8</td>
<td>250-300*</td>
<td>.003</td>
<td>0.06</td>
</tr>
</tbody>
</table>

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General soil characteristics

Texture: sandy loam
Porosity ($\Theta_s$): 0.45
Wilting point potential ($\Psi_w$): -15 bars
Anaerobiosis point potential ($\Psi_a$): -0.3 bars

Root zone characteristics

<table>
<thead>
<tr>
<th>Depth [cm]</th>
<th>% Active roots (summer/winter)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-10</td>
<td>47 / 80</td>
</tr>
<tr>
<td>10-20</td>
<td>23 / 20</td>
</tr>
<tr>
<td>20-30</td>
<td>12 / 0</td>
</tr>
<tr>
<td>30-40</td>
<td>11 / 0</td>
</tr>
<tr>
<td>40-80</td>
<td>7 / 0</td>
</tr>
</tbody>
</table>

Surface flow parameters

<table>
<thead>
<tr>
<th>Regime</th>
<th>Roughness [$m^{0.5}$/hr]</th>
<th>Exponent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overland</td>
<td>2.5e3</td>
<td>1.5</td>
</tr>
<tr>
<td>Channel</td>
<td>1.0e5</td>
<td>1.5</td>
</tr>
</tbody>
</table>

*=variable bottom

II. Validation run for soil moisture.

Shown are means and gradients on the divergent hillslope the period Nov 1-Dec 12, 1991, for 0-90 cm depth. Major events occurred Nov 22-25 and Nov 28-Dec 3. Abscissa is meters from stream; ordinate is fractional soil moisture content. Circles are measured values (mean of 3 replicates) triangles are simulated results. Solid line is regression on measured data; dashed line is regression on simulated data.