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13. ABSTRACT (Maximum 200 words)

This final report describes the research accomplishments of a one year project that was conducted at the Pennsylvania State University. Work on this project continues under a related four year grant at Colorado State University. The primary objective of the first year of this project was to develop the base of knowledge necessary to devise an interpolation or downscaling method for soil moisture data that accounts for the role of topography. In order to achieve this long-term objective, the project examined the statistical properties of both observed and simulated soil moisture fields. Soil moisture was analyzed at a given scale and over a range of scales. A probability-distributed model was developed to relate space-time mean soil moisture to climatic forcing as well as runoff and evapotranspiration. Laboratory experiments of basin evolution were analyzed to gain a better understanding of topographic scaling and its origin, and a numerical landscape evolution model was devised that incorporates subsurface flow. The model was used to study the impact of subsurface flow in landscape dynamics and the evolution of saturated areas over time.

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Publications

Peer-Reviewed Papers

Niemann, J.D., and E.A.B. Eltahir, 2003, “Prediction of Regional Water Balance Components Based on Climate, Soil, and Vegetation Parameters, With Application to the Illinois River Basin,” *Water Resources Research*, 40(3), W03103, DOI: 10.1029/2003WR002806.

Niemann, J.D., R.L. Bras, and D. Veneziano, 2003, “A physically-based interpolation method for fluvially eroded topography,” *Water Resources Research*, 39(1), 1017, DOI: 10.1029/2001WR001050.

Non-Peer Reviewed Papers

Niemann, J.D., and E. Kirby, 2003, “Geomorphology,” *Geotimes*, American Geological Institute, July Issue, pp. 14-15.

Papers Presented at Conferences and Meetings

Niemann, J.D., E.A.B. Eltahir, and X. Huang, April 2004, “Interactions of Soil Moisture and Topography Across a Range of Scales,” Army Research Office, Arid Lands Hydrology and Geomorphology Workshop, Fort Carson, Colorado.

Huang, X., and J.D. Niemann, March 2004, “Numerical Simulation of Groundwater Recharge and Discharge in Escarpment Retreat,” American Geophysical Union Hydrology Days, Fort Collins, Colorado.

Niemann, J.D., and E.A.B. Eltahir, March 2004, “On the Sensitivity of Regional Hydrologic Fluxes to Climatic Changes,” American Geophysical Union Hydrology Days, Fort Collins, Colorado.

Niemann, J.D., and L. Hasbargen, March 2004, “A Comparison of the Geometrical Properties of Experimental and Natural River Basins Across a Range of Scales,” American Geophysical Union Hydrology Days, Fort Collins, Colorado.

Huang, X., and J.D. Niemann, December 2003, “Impacts of Groundwater Dynamics on Landscape Evolution,” American Geophysical Union Fall Meeting, San Francisco, California.

Niemann, J.D., and E.A.B. Eltahir, December 2003, “Impacts of Climate Change on Regional Water Balance, With Application to the Illinois River Basin,” American Geophysical Union Fall Meeting, San Francisco, California.

Reed, P.M., C.J. Duffy, D.F. Hill, P.A Johnson, A.C. Miller, and J.D. Niemann, April 2003, “Addressing Water Resources at Risk: A Systems Approach for Decision Support,” Keystone Alliance Summit on Homeland Security, Pennsylvania State University.

Niemann, J.D., and L. Hasbargen, December 2002, "Scaling Properties of Laboratory-Generated Stream Networks," American Geophysical Union Fall Meeting, San Francisco, California.

Invited Lectures and Seminars

Niemann, J.D., November 2003, "Self-Similarity of River Basins and Applications to Geomorphic Modeling and Topographic Interpolation," Department of Civil, Environmental, and Architectural Engineering, University of Colorado, Boulder.

Niemann, J.D., May 2003, "Water Resources Engineering for an Orphanage in Guatemala," Water Resources Engineering Seminar, Department of Civil and Environmental Engineering, Pennsylvania State University.

Niemann, J.D., March 2003, "Fractals and Scaling Invariance in Hydrology," Department of Civil and Environmental Engineering, Pennsylvania State University.

Niemann, J.D., R.L. Bras, E.A.B. Eltahir, and D. Veneziano, January 2003, "Physically-Based Self-Similarity of River Basin Topography and Applications to Geomorphic and Hydrologic Modeling," Department of Civil Engineering, Colorado State University.

Manuscripts Submitted for Publication

Niemann, J.D., and L.E. Hasbargen, in review, "A Comparison of Experimental and Natural Drainage Basin Morphology Across a Range of Scales," *Journal of Geophysical Research*.

Manuscripts in Preparation (Submission is expected within 1 month)

Niemann, J.D., and E.A.B. Eltahir, in preparation, "Sensitivity of Regional Water Balance Components to Climatic Changes, With Application to the Illinois River Basin," to be submitted to *Advances in Water Resources*.

Huang, X. and J.D. Niemann, in preparation, "The Role of Groundwater Dynamics in the Evolution of River Basin Hydrology and Topography," to be submitted to *Journal of Geophysical Research*.

Niemann, J.D., in preparation, "Drainage Nets," *The Encyclopedia of Water*, John Wiley and Sons.

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Statement of Problem and Most Important Results

Forward

This report describes the research accomplishments of the project "Scaling Properties and Spatial Interpolation of Soil Moisture" conducted at Pennsylvania State University. The planned duration of this project was five years, but the principal investigator relocated from Pennsylvania State University to Colorado State University after approximately one year. Consequently, the grant at Pennsylvania State University was terminated in May 2004 after one year of funding, and a new grant was issued at Colorado State University for the remaining four years of the project. This final report describes the progress made during the first year of the five-year project.

1 Problem Statement

Soil moisture patterns play an important role in numerous hydrologic and geomorphic applications. They directly impact many hydrologic processes including infiltration, surface runoff, transpiration, and recharge. Through these processes, soil moisture patterns also influence precipitation recycling within a region, thus perpetuating wet and dry periods (Findell and Eltahir, 1997). Soil moisture also impacts, either directly or indirectly, geomorphic processes such as bedrock weathering and sediment detachment, transport, and deposition.

Despite these important roles, soil moisture patterns and dynamics are not well understood. The difficulty in understanding soil moisture arises from two sources. First, soil moisture patterns and dynamics are very complex, and variability occurs over a wide range of spatial and temporal scales. At large spatial scales, soil moisture depends largely on climatic characteristics and soil types, but at smaller scales, topography becomes more important in determining soil moisture patterns. Furthermore, the roles of these physical characteristics can vary in time. During dry periods, soil type is more important in determining soil moisture patterns, whereas in wet periods, the role of topography is enhanced (Grayson et al., 1997; Western et al., 2001). Soil moisture patterns and dynamics also depend on the depth over which the moisture is considered. Near the surface, soil moisture is highly dynamic, but it becomes less dynamic with increasing depth. The proximity of the water table also impacts the nature of the variability with depth (Salvucci and Entekhabi, 1994a, 1994b).

The second difficulty in characterizing soil moisture is measurement (see Robock et al., 2000). Numerous in-situ methods are available to characterize soil moisture (neutron probes, for example), but such methods quantify soil moisture only at the sampling locations. Due to the large and complex spatial variability observed, such measurements are not easy to extrapolate to the spatial scales of most hydrologic and geomorphic applications. Alternatively, remote sensing methods can be used to measure soil moisture, either by aircraft or satellite. Most such methods rely on passive microwave measurements. Unfortunately, remote sensing methods characterize soil moisture only near the ground surface and provide measurements at a relatively coarse resolution.

2 Project Objectives

The long-term objective of this research project is to develop an interpolation or downscaling method for soil moisture observations that accounts for the role of topography. To accomplish this primary objective, several secondary goals must be achieved. First, a better understanding of soil moisture patterns is required, which includes characterizing the spatial and temporal variability as well as their dependence on the scale of observation. Ultimately, one would like the ability to simulate the soil moisture variability in space and time using climatic inputs. Second, the dependence of soil moisture patterns on a region's physical characteristics must be analyzed. This goal involves describing how soil moisture patterns depend on variables such as soil type and topography at different scales. Ultimately, the connections between topographic and soil moisture scaling characteristics are sought. Third, a better understanding of the scaling characteristics of topography and their dynamic origins is needed. In particular, one would like to quantify the relationship between the subsurface redistribution of water and geomorphic processes and river basin form. In the end, this understanding will guide the development of soil moisture interpolation procedures that include the role of topography.

3 Approach

The general approach used in this project was a combination of statistical analysis of digital data, numerical and analytical modeling of soil moisture, and numerical modeling of topographic dynamics. Soil moisture data from three sources was used: the Illinois State Water Survey data set, the Southern Great Plains experiment in 1997 (SGP 97), and the Washita experiment in 1992 (Robock et al., 2000). The Illinois data was collected with an in-situ method (neutron probes) and describes the soil moisture with only crude spatial detail. However, this dataset has a long duration (approximately 20 years), so it is well-suited for detailed studies of soil moisture dynamics. The SGP 97 data and the Washita data were primarily collected with aircraft-based remote sensing methods, but in-situ methods were used to ground-truth the data. These datasets have good spatial resolution, but limited duration. The experiments collected data over a period of a few days to weeks. The Washita dataset describes a subset of the SGP 97 field site. All of these datasets describe regions with semi-humid temperate climates and low relief.

Three primary methods of statistical analysis were used. First, basic statistical properties of the soil moisture patterns were measured. This approach largely neglects spatial and temporal correlations and connectivity for simplicity. Second, Empirical Orthogonal Functions (EOFs) were extracted from the soil moisture data and compared with ancillary data. This approach allows one to identify the dependence of soil moisture on other physical characteristics of the region. Third, scaling analyses were used to examine how the basic properties of soil moisture change with the scale of observation.

The modeling of soil moisture was based on local-instantaneous descriptions of hydrologic processes such as infiltration, evapotranspiration, and recharge. The model describes these inflows and outflows from the vadose zone as a function of the local-instantaneous soil moisture. These models can be used to describe the local dynamics of soil moisture or they can be integrated over spatial and temporal probability distributions to describe the large-scale, long-term behavior.

The geomorphic model used is a fully-distributed numerical model. This model was extended to include a more detailed hydrologic description of subsurface flow. As a result, it can describe the occurrence and distribution of saturated areas, their relation to runoff production, and their influence on topographic form and dynamics.

4 Main Results

4.1 Statistical Analysis of Soil Moisture in Space and Time

The Illinois dataset was used to gain a better understanding of the variability of soil moisture in space and time at a relatively large scale. This analysis considered soil saturation (the soil moisture divided by the porosity) measured 0-10 cm below the ground surface. The observations at each gage were treated as independent and identically distributed random variables, which is supported by the low correlations observed between the measurements at different gages. Under this assumption, the soil moisture can be fully described by a single probability density function (PDF). We hypothesized that this spatial PDF conforms to an Erlang distribution and tested this hypothesis with the Kolmogorov-Smirnov (KS) test. This hypothesis is acceptable for 89% of the sample distributions at the 10% level of significance. Furthermore, we hypothesized that the shape parameter of the Erlang distribution remains constant for the spatial distributions. If this hypothesis holds, then the soil moisture patterns become more variable in space when they are wetter on average. The KS test accepts the hypothesis that the samples are drawn from an Erlang distribution with a constant shape parameter for 94% of the samples at the 10% level. A higher percentage of samples can be accepted for this more restrictive case because the KS test measures only the largest deviation between the sample distribution and the hypothesized distribution, whereas the parameter estimation procedure minimizes the error for the distribution as a whole.

The Illinois data were also used to investigate the temporal variability of the spatial mean soil saturation. Again, independence between spatial mean soil saturation at different times was assumed. Two types of analyses were performed. First, the distribution of mean soil saturation was considered within a given year. From this perspective, the parameters of the distribution (e.g., space-time mean soil saturation) can be specified for each year, but the within-year variability is described by the distribution. We hypothesized that the PDF conforms to a beta distribution. At the 10% level of significance, 100% of the temporal distributions passed the test. It was also observed that the standard deviation of the temporal distribution remains approximately constant. Using the KS test again, 90% of the samples were found to conform to a beta distribution with constant standard deviation at the 10% level of significance. The second analysis considered the distribution for spatial mean soil saturation when all temporal variability is included. This distribution includes both within-year and inter-annual variability. Thus, this distribution describes the region's climate. Again, we hypothesized that a beta distribution characterizes the distribution, and this hypothesis was accepted at the 10% level. Figure 1 compares the sample temporal distribution of the spatial mean soil saturation with the beta distribution. A close similarity between the two cumulative distribution functions is observed. The fact that the beta distribution characterizes both the within-year variability and the total variability is not surprising. The mean standard deviation for the within-year distribution is 0.162 and the standard deviation for the climatic distribution is 0.173. The similarity of these two numbers implies that the bulk of the variability of soil saturation in time arises from within-year variations.

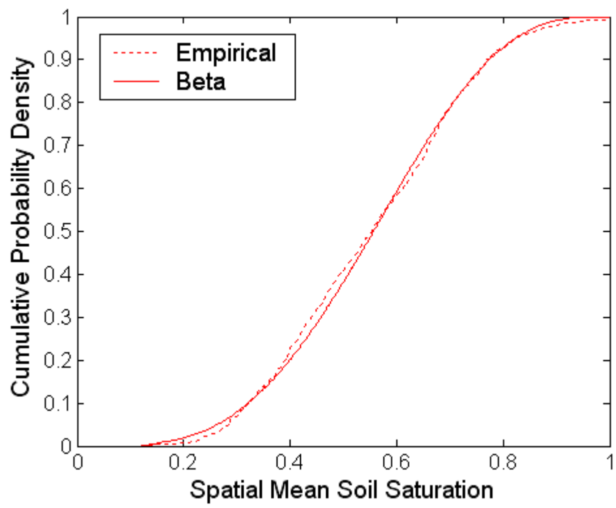

Figure 1. Temporal cumulative distribution function of spatial mean soil saturation from the Illinois dataset along with a beta distribution

Probabilistic modeling of soil saturation is simplified because both the spatial distribution's shape parameter and the temporal distribution's standard deviation remain relatively constant in time. In particular, if the mean value of either distribution is known, then all characteristics of the PDF can be determined.

The correlations between the spatial mean soil moisture and the spatial mean precipitation and spatial mean potential evapotranspiration (PET) were also investigated. The correlation between the mean soil saturation and precipitation was 0.16, which suggests that the soil saturation tends to be larger when the region receives more precipitation (as one would expect). The correlation is low because the precipitation rate is highly variable in time whereas the soil saturation is less variable. The correlation between the soil saturation and PET is -0.54. The negative value implies that the soil saturation tends to be low when the PET is high. This result is also expected because PET influences the loss of soil moisture through evapotranspiration. Understanding these correlations allows consideration of the joint distributions of soil moisture and precipitation and soil moisture and PET in a probabilistic model. A more detailed account of this data analysis can be found in Niemann and Eltahir (2004) and Niemann and Eltahir (in prep.).

4.2 Modeling Soil Moisture and Regional Water Balance

The statistical analysis of soil moisture in the previous sections was used to develop a simple model for soil moisture and regional water balance components. The general approach of this model is to divide the region into recharge and discharge locations. Recharge locations can be saturated or unsaturated but always have hydraulic gradients oriented to allow recharge to the groundwater. Discharge locations are assumed to be saturated and have gradients oriented to allow groundwater discharge at the surface. The fluxes in and out of the vadose zone are first described at the local and instantaneous scales for the recharge and discharge locations. Then, they are integrated over the spatial and temporal distributions of soil saturation, precipitation, and PET to determine relations between the space-time means of precipitation, PET, soil saturation, evapotranspiration, surface runoff, and groundwater discharge.

The model for infiltration rate F can be written as:

$$F = \begin{cases} \alpha(1-s) + K_h & \text{Recharge Locations} \\ 0 & \text{Discharge Locations} \end{cases} \tag{1}$$

where α is an infiltrability parameter, s is the soil saturation, and K_h is the saturated hydraulic conductivity. Similar expressions have been used previously (e.g. Rodriguez-Iturbe et al., 1999), but this expression allows infiltration for saturated soil. Given this infiltration model, the local-instantaneous surface runoff R can be written:

$$R = \begin{cases} P - F & \text{if } P > F \\ 0 & \text{if } P \le F \end{cases} \tag{2}$$

where P is the local-instantaneous precipitation rate. Coupling Equations (1) and (2) shows that runoff can occur because α and K_h are small (Horton Runoff) or s is large (Dunne Runoff).

Two losses from the vadose zone are allowed. The first is recharge to the aquifer. The recharge G can be modeled as:

$$G = \begin{cases} K_h s^{\gamma} & \text{Recharge Locations} \\ 0 & \text{Discharge Locations} \end{cases} \tag{3}$$

where γ is an exponent that depends on soil type. This recharge expression can be derived from Darcy's law if the elevation change dominates the hydraulic gradient and the Campbell (1974) equation is used to describe unsaturated hydraulic conductivity. The second loss is the evapotranspiration from the soil. If the soil saturation is above the wilting point β, it is assumed that the evapotranspiration is equal to the PET. Below the wilting point, the evapotranspiration depends on the soil saturation. In particular:

$$E = \begin{cases} E_p s / \beta & \text{if } 0 \le s < \beta \\ E_p & \text{if } \beta \le \mathrm{s} \le 1 \end{cases} \tag{4}$$

Similar approaches have been used previously to describe the losses from the vadose zone (e.g., Dooge et al., 1999), and the combined loss function described by Equations (3) and (4) is supported by observations from Illinois (Salvucci, 2001).

After integrating over the spatial distributions, analytical expressions were obtained for the spatial mean surface runoff, evapotranspiration, and groundwater recharge as a function of the spatial mean soil saturation. Then, by integrating over the temporal distributions of the spatial means, similar relationships were determined for the space-time mean values. By applying equilibrium conditions for the groundwater and the system as a whole, the space-time mean soil saturation can be determined from the space-time mean precipitation, PET, and saturated hydraulic conductivity. These equilibrium conditions hold in approximation at the annual and climatic time scales. Figure 2a compares the annual runoff determined from the model with annual runoff observations from Illinois. The figure shows that the model captures the basic tendency of the observations. In this model, only precipitation was varied as an input, so the scatter observed in this plot cannot be reproduced. The figure also shows the relative contributions of surface runoff and groundwater discharge to the total runoff (distinguished by a dotted line). Figure 2b graphs the dependence of the runoff coefficient on the humidity index D_E, which is defined as the mean precipitation divided by the mean PET. Several empirical expressions have been proposed that describe the observed variation of the runoff coefficient between different regions or years as a function of the humidity index (Dooge, 1992). The runoff coefficient calculated by the model actually depends on two humidity indices: D_E and D_K, where D_K is the mean precipitation divided by the saturated hydraulic conductivity. The blue lines in Figure 2b demonstrate that the model's dependence on D_E is similar to Schreiber's empirical equation. As the humidity index becomes large, the evapotranspiration is not restricted by the availability of water at as many locations and times. As a result, the evapotranspiration rate approaches the PET rate, which constrains its ability to transport water. This restriction leads to an increase in mean soil saturation, which promotes Dunne runoff and thus higher runoff coefficients.

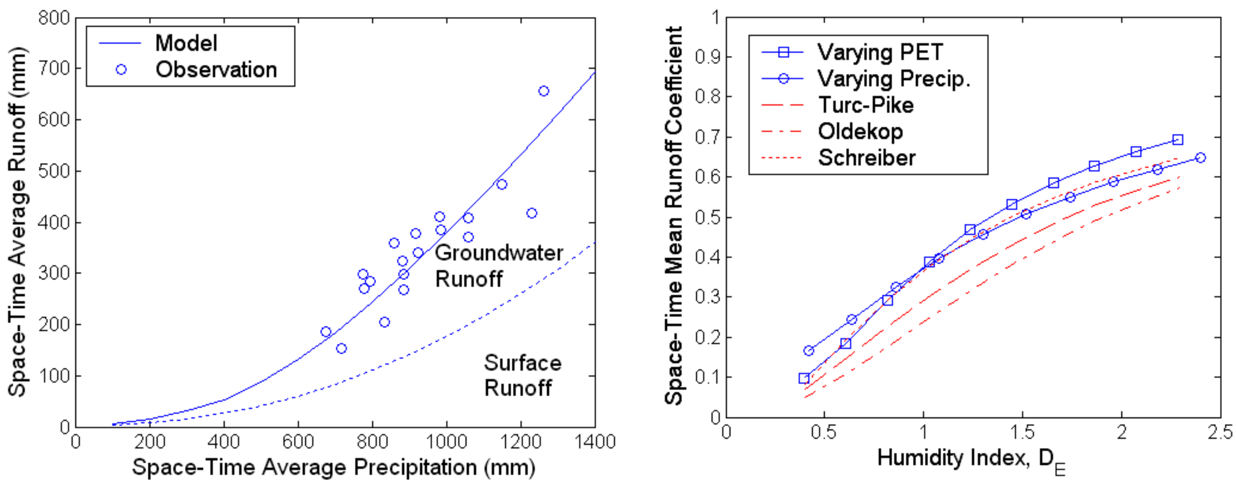

Figure 2. (a) Comparison of observed annual runoff from Illinois with model predictions, and (b) comparison of modeled runoff coefficient with three empirical equations

Another key result from the model is the nature of the relationship between the soil saturation and the hydrologic and physical characteristics of the region. Figure 3 shows the derived relationship between the mean soil saturation and the two humidity indices D_E and D_K. As the precipitation becomes larger with respect to either PET or saturated hydraulic conductivity, the mean soil saturation increases as expected. The nature of this increase can be classified into three regimes. When D_E is low, the value of the hydraulic conductivity has very little influence on the mean soil saturation, so the region is D_E controlled. In this regime, evapotranspiration is the dominant loss from the vadose zone. Similarly, when D_K is small, the hydraulic conductivity is large, so groundwater recharge becomes a major loss. However, even for very low D_K values, the influence of evapotranspiration is observed. In the third regime, evapotranspiration is the dominant loss, but groundwater recharge is also significant. This zone is considered D_E dominated. See Niemann and Eltahir (2004) for more details on this subject.

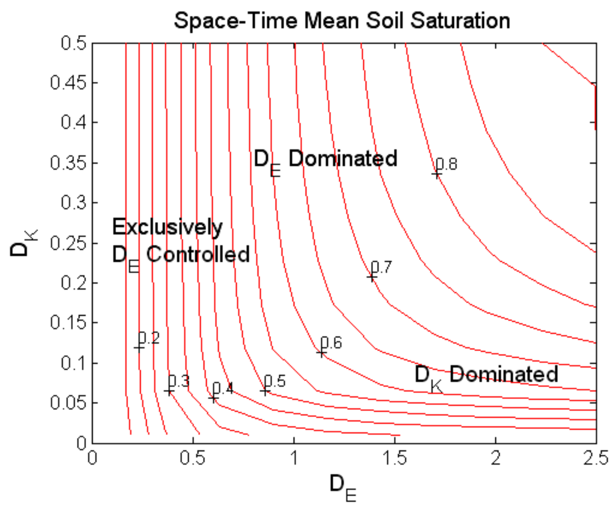

Figure 3. Estimation of space-time mean soil saturation from precipitation, PET, and hydraulic conductivity

The modeling approach was also used to understand the impact of a region's physical and statistical characteristics on the mean soil saturation and water balance components. In particular, we examined the sensitivity of soil moisture, surface runoff, and groundwater discharge to changes in precipitation and PET. The sensitivity is defined as the percentage change in a variable when the mean precipitation or PET is changed by one percent (Schaake, 1990; Sankarasubramanian et al., 2001). Analysis of the sensitivities is useful not only for characterizing soil moisture but also for forecasting the vulnerability of a region's water cycle to climate changes. Figure 4 plots the sensitivity of mean soil saturation, surface runoff, and groundwater discharge to changes in PET. The sensitivities are calculated for regions that differ only in their wilting point (β) or their temporal standard deviation of soil saturation (σ). The figure shows that regions with higher wilting points have less sensitive mean soil saturations. When the wilting point is large, the evapotranspiration is more limited by moisture availability, so the fluxes and soil moisture are less sensitive to changes in PET. The figure also shows that regions with more temporal variability of soil saturation have less sensitive surface and groundwater runoff and slightly more sensitive soil saturation. Temporal variability of soil saturation smoothes out thresholds in the partitioning of local-instantaneous precipitation. Thus, more variability in soil moisture results in smoother relations and less sensitivity of the fluxes. A more detailed description of the sensitivity of soil moisture can be found in Niemann and Eltahir (in prep.).

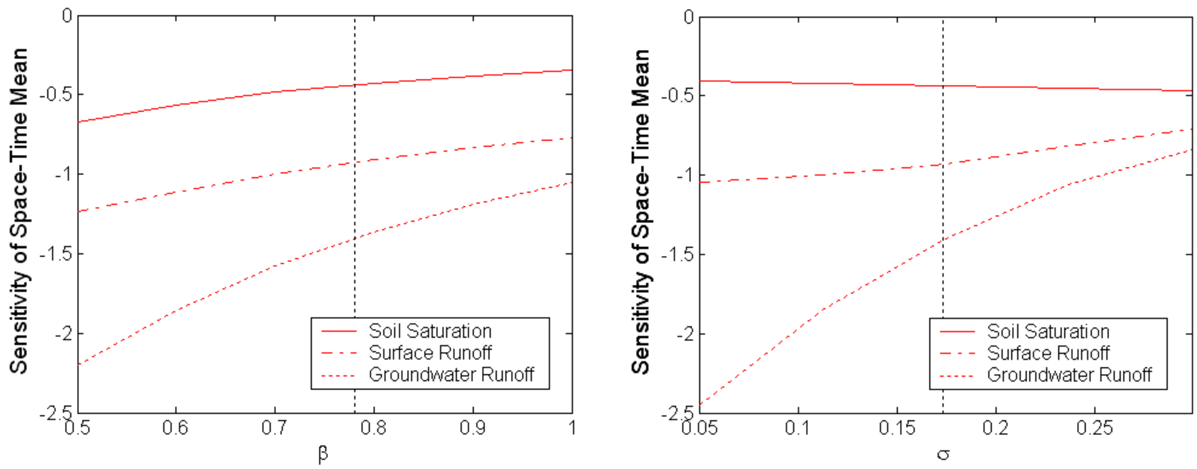

Figure 4. Sensitivity of space-time mean soil saturation and hydrologic fluxes to changes in PET as the wilting point (β) and the temporal standard deviation of soil saturation (σ) are changed.

4.3 Dependence of Soil Moisture on Regional Characteristics

The previous subsections described some statistical properties of soil moisture and presented a model that relates soil moisture to precipitation, PET, and losses from the vadose zone. In this subsection, the observed dependence of soil saturation on other physical characteristics of a region are analyzed.

Soil saturation patterns are thought to have a complex dependence on regional topography, soil type, and vegetation. The SGP 97 soil saturation data have a high degree of variability in both space and time. In this project, we hypothesized that this variability can be well described by a small number of underlying independent spatial patterns. These patterns are thought to reflect certain characteristics of the region such as percent sand, percent clay, surface roughness, bulk density, and vegetation water content. However, the connections between these patterns and the regional characteristics may depend upon the spatial and temporal scales considered.

Empirical Orthogonal Function (EOF) and Principal Component (PC) analysis was used to describe the total variability from a 16 day time series of observations. The type of variability explained by EOF analysis depends on the preparation of the data. We have analyzed the SGP 97 in two ways. First, the average soil saturation value was found for the time series at each grid point and removed to calculate temporal soil saturation anomalies. The resulting EOFs are spatial patterns (maps), explaining the variability the grid points relative to their long-term averages. Second, the data was analyzed in spatial anomaly form by removing the spatial average on each day from every grid point. When the data is placed into spatial anomaly form, the EOFs are maps explaining the variability of each grid point relative to the spatial average.

EOF analysis is based on the notion that a data matrix X (e.g. spatial soil saturation anomalies) can be decomposed into PCs, eigenvalues, and EOFs. In particular:

$$X = UEV^{T} \tag{5}$$

where the columns of U contain the PCs, the diagonal values of E contain the squares of the eigenvalues, and the rows of V contain the EOFs. The principle components relate to the temporal behavior, the eigenvalues are used to rank the significance of the EOF/PC pairs, and the EOFs relate to the spatial patterns. Soil saturation anomalies were analyzed to find EOFs by first multiplying the anomalies matrix by its transpose to find the autocorrelation matrix. This autocorrelation matrix can be analyzed to find eigenvectors (corresponding to the PCs) and eigenvalues. To remove any nonphysical amplitude that results from the eigenanalysis, the PCs were standardized to have a mean of zero and a standard deviation of one. By multiplying the standardized PCs with the original anomaly matrix, one can find the EOFs, which have the same units as the original data. The variance explained by each of the EOFs is equal to the corresponding eigenvalue divided by the sum of all the eigenvalues. EOF/PC pairs are considered significant if there is no overlap of their error bar plots. Error bars are determined by the fraction of variance explained (λ) plus or minus $(\lambda(2/N)^{1/2})/2$ where N is equal to the number of independent samples (taken as the number of days in the time series).

When the soil saturation data (in temporal anomaly form) were analyzed, five significant EOF/PC pairs were found. Together they explain 94% of the variance in the original data, and 50% of the variance is explained by temporal EOF 1 alone. When the data were analyzed a second time in spatial anomaly form, five significant EOF/PC pairs were also found which together explain 94% of the variance. However, the first spatial EOF explains only 61% of the variance. Spatial EOF 1 is shown in Figure 5 along with the soil saturation pattern from June 18 and the pattern of percent sand.

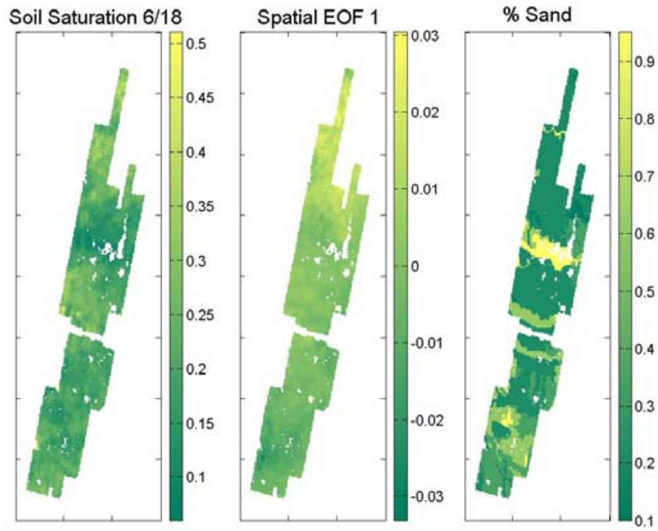

Figure 5: A sample map of soil saturation data, spatial EOF 1, and percent sand for visual comparison.

EOF analysis can be performed in a variety of ways, depending on one's objectives. We have found the EOFs and PCs from a data matrix that contains only the soil saturation fields. Kim and Barros (2002) also generated EOFs and PCs using the SGP 97 data. Their EOF analysis was performed using a matrix with soil saturation, vegetation water content, percent sand and topography. Their EOFs illustrate patterns that captured the interdependencies of each of these variables. The EOFs we calculated describe the spatial and temporal variability of soil saturation in terms of a small number of independent spatial patterns.

The correlation coefficient is a common way to determine whether two variables have a linear dependency. We have used it to measure how closely our EOFs are related to the physical characteristics of the region. When the analysis was performed on spatial EOF 1, it was found to have a correlation coefficient of -0.32 with percent sand, 0.04 with percent clay, -0.07 with surface roughness, -0.20 with vegetation water content, and -0.20 with bulk density. The high (negative) correlation with percent sand is an expected result. For example, visual inspection shows that the southern portion of the region tends to have high percent sand values and low EOF 1 values (Figure 5).

The SGP 97 data itself was correlated on a daily basis with regional characteristics by Kim and Barros (2002). They found that on 'wet' days, soil saturation was most highly correlated with percent sand, while on 'dry' days it was most highly correlated with percent clay. They also found that each of the ancillary data correlations increased with aggregation. In contrast, our research has found a set of EOF maps that efficiently describe the variability of soil saturation for the duration of SGP 97 experiment. The most significant of these maps is highly correlated with percent sand, but not well correlated with percent clay.

The correlation analysis described above was performed with the data at the original pixel size of 0.64 km^2. Thus, the analysis includes spatial variability from a wide range of spatial scales (from 0.64 km^2 to nearly the size of the domain). To determine which variables are related to the spatial pattern of EOF 1 at different scales, we repeated the correlation analysis on aggregated data. Both the EOFs and the regional characteristic data were aggregated from an original cell size of 0.64km^2 up to a cell size of 1024km^2. Figure 6 shows the results of this analysis. The correlation of EOF 1 with percent sand, percent bulk density, and vegetation water content increases slightly with increasing aggregation. The correlation of EOF 1 with percent clay starts out slightly positive but turns slightly negative as the aggregation scale increases. A dramatic increase in the correlation of EOF 1 and surface roughness is observed with increasing scale. A visual inspection on aggregated maps of EOF 1 and surface roughness revealed that locations with low surface roughness also have low values for EOF 1. The observed positive correlation at large scales may be associated with the fact that smooth topography increases the potential for evapotranspiration. Smooth topography is more uniformly oriented towards the sun and therefore receives more radiation.

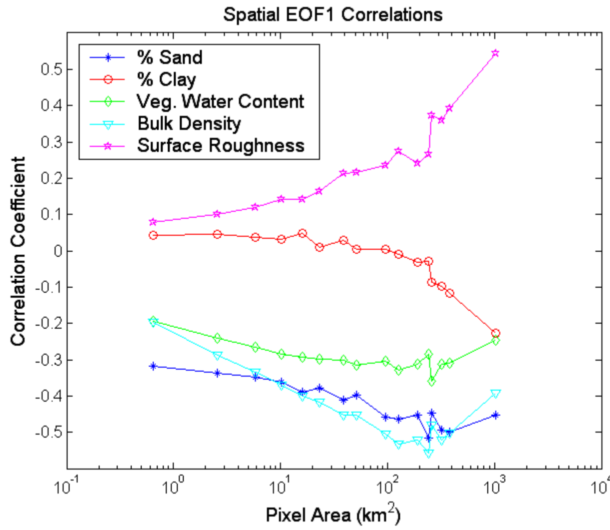

Figure 6. Correlation coefficients of spatial EOF 1 with regional characteristics at a range of scales.

Another project objective is to understand the relationship between the scaling properties of topography and those of soil saturation. Numerous indices are available to estimate the relative soil wetness of a location from topographic information. These indices usually determine the soil saturation (or a proxy) as a deterministic function of topography and other data (e.g., O'Loughlin, 1986). One such index is the so-called Topindex (Beven and Kirkby, 1979), which we used to analyze the relationship between the scaling properties of topography and those of soil saturation. A well-known implication of the scaling invariance of topography is the so-called slope-area relationship (Veneziano and Niemann, 2000), which states that the slope of a channel decreases as the topographic area that drains through the channel increases. In particular, $S \approx bA^{-\theta}$ where S is channel slope, A is the drained area, b is a coefficient, and θ is an exponent that typically falls within $0.2 \le \theta \le 0.6$ (Veneziano and Niemann, 2000). Figure 7 plots the Topindex as a function of drained area ("sub-basin area"). The figure shows three distinct segments in this relationship. When the area draining through the point is small, the point is located on a hillslope and the Topindex exhibits little dependence on the drained area. As the drained area increases, the points are located in unchannelized valleys and in ephemeral streams and a power law is observed. At very large drained areas, the points fall within perennial channels and the Topindex reaches a maximum saturated value. Analytical expressions were also derived that describe the shape of this scaling relationship in terms of the parameters of a common landscape evolution model (from Moglen and Bras, 1995).

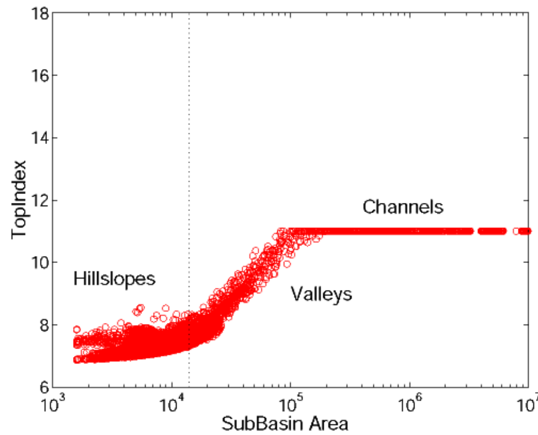

Figure 7. Scaling of Topindex with sub-basin or drained area

4.4 Topographic Scaling Invariance and Its Origin

Another line of research was an investigation of the origin and nature of topographic scaling invariance. Understanding topographic scaling is important if this condition is to be used to infer fine-scale soil moisture in part from coarse-scale topographic information. As part of this line of research, the scaling properties of a series of laboratory-generated topographies were analyzed (Hasbargen and Paola, 2000). These topographies were generated under controlled rainfall rates, uplift rates, and substrate characteristics. Under most cases considered, the substrate was kept saturated, so the runoff production was constant in space and time. One of the key results from these laboratory experiments was an observed mobility of the channels even when the denudation rate balanced the uplift rate on average. Under such conditions, most numerical landscape evolution models produce temporally invariant surfaces (Hasbargen and Paola, 2000). We examined the scaling-invariance of topographies generated under these conditions and compared it with the scaling-invariance of typical natural basins. Our analysis identified a quantitative scaling property that coincided with the mobility of channels. In particular, small tributaries near large channels typically have lower slopes than expected from the mean slope-area relationship for the experiments that exhibited mobility. Figure 8 demonstrates this tendency. The left column of plots shows the slope-area coefficient as function of the ratio of a nearby channel's drained area and the local drained area. For the Madulce basin in California the coefficient is independent of this ratio of areas. For the laboratory experiments (both 5 and 6), the coefficient decreases slightly as the ratio increases. This decrease implies that the presence of nearby large channels results in smaller slopes for small channels. The right column of plots displays the same analysis but the drained areas are determined after moving specified distances upstream. The dependence disappears with increased distance in Experiment 5, which had less lateral movement, but it remains visible for Experiment 6, which had more lateral movement. This property and other scaling characteristics of laboratory and natural basins are described in Niemann and Hasbargen (in review).

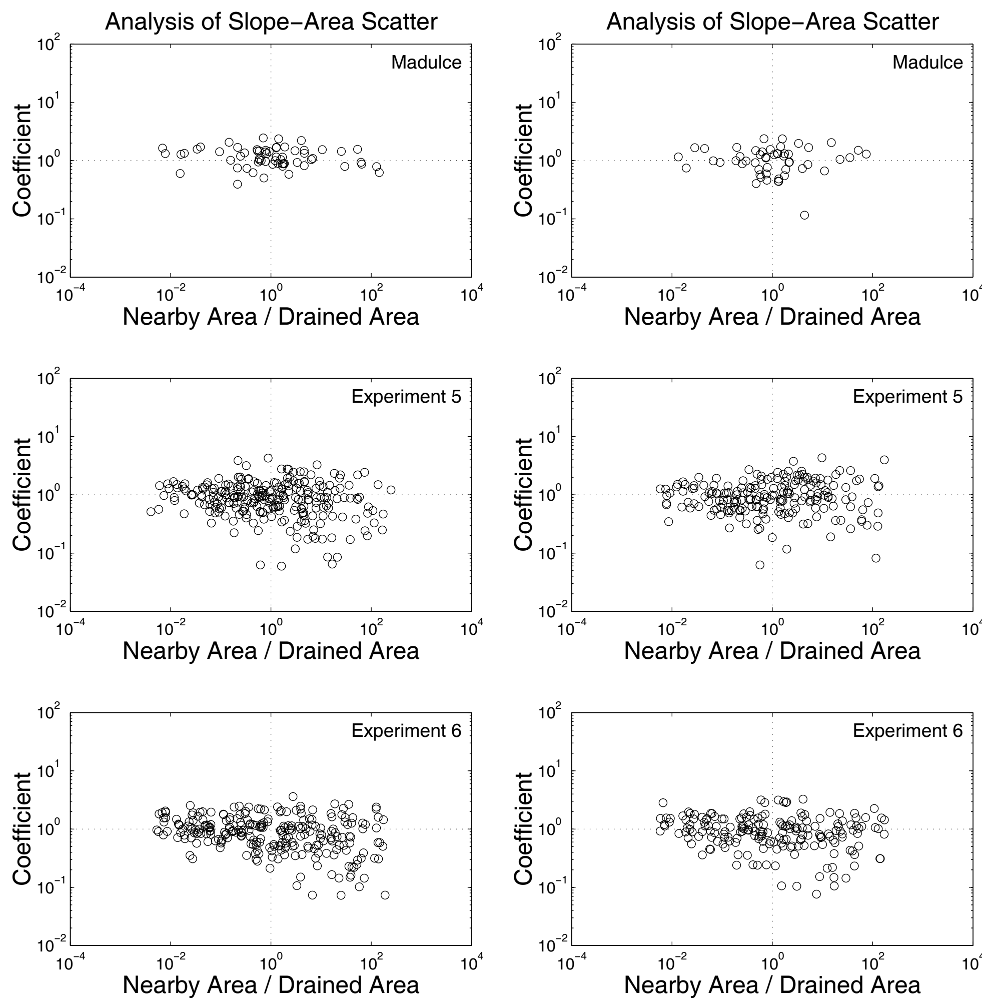

Figure 8. Dependence of secondary tributary slopes on primary tributary slopes.

4.5 Relationship between Subsurface Flow and Topographic Dynamics

The final line of research examined the impact of subsurface flow on the evolution of topographic scaling and the associated evolution of hydrologic processes. The general approach used to study these issues was the development of an improved numerical landscape evolution model. The main improvement lies in the description of the hydrologic processes. In particular, infiltration and groundwater dynamics have been included when determining runoff production and streamflow.

The erosion model used is a variant of the GOLEM landscape evolution model (Tucker and Slingerland, 1997). The governing equation under the detachment-limited condition can be written:

$$\frac{\partial z}{\partial t} = U - kQ^m S^n + D\nabla^2 z \tag{6}$$

where z is elevation, t is time, U is uplift rate, k is an erodability coefficient, Q is water discharge, S is channel slope, m and n are exponents, and D is the hillslope diffusivity. In most landscape evolution models, the discharge rate Q is calculated from:

$$Q = P_e A \tag{7}$$

where P_e is an effective precipitation rate and A is the drained area. P_e is spatially uniform, which disallows Dunne runoff production and groundwater discharge.

In the improved model, runoff production and groundwater discharge are determined dynamically. Precipitation is simulated as a series of discrete storm events using the rectangular pulse model (Eagleson, 1978; Tucker and Bras, 2000), which includes three independent random variables: rainfall intensity P, rainfall duration T_P, and inter-storm period T_0. Runoff and infiltration are determined using a model similar to the one described earlier in this report. However, in these preliminary simulations, infiltration and recharge rates are assumed to be independent of the soil saturation for simplicity. The groundwater is simulated using the Dupuit approximation, which assumes that the hydraulic gradient coincides with the water table and the groundwater flow is mainly horizontal. Under these assumptions the water table level h is governed by the expression:

$$S_y \frac{\partial h}{\partial t} = \frac{K_h}{2}\left[\frac{\partial^2 (h^2)}{\partial x^2} + \frac{\partial^2 (h^2)}{\partial y^2}\right] + F \tag{8}$$

where x and y are the horizontal coordinates and S_y is the specific yield. This expression assumes that the underlying impermeable layer is horizontal (for simplicity of notation), but the numerical model can include spatial variations in the elevation of this layer as well. Groundwater discharge occurs at locations where the water table meets the land surface. The total streamflow is the sum of the surface runoff and groundwater discharge.

Figure 9 shows a series of simulated precipitation events along with the streamflow produced by the model. The streamflow exhibits spikes, which are associated with the surface runoff from precipitation events, and base flow, which is associated with groundwater discharge.

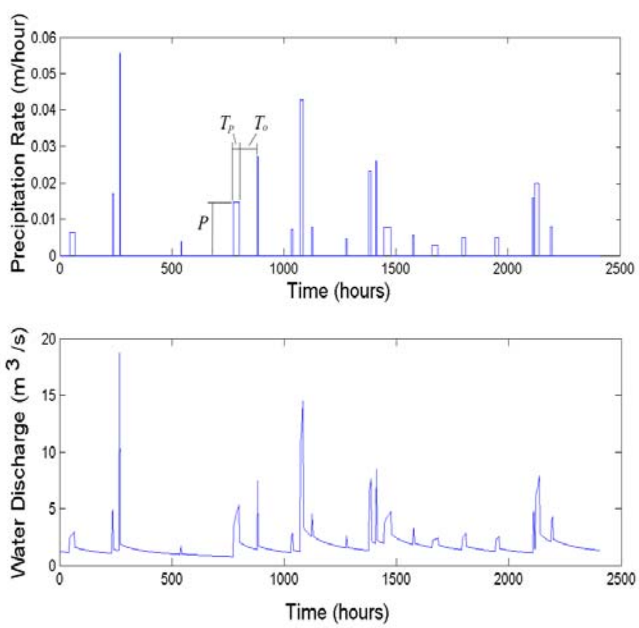

Figure 9. Simulated precipitation and the associated streamflow at the simulated region's outlet

The model has been used to investigate the impact of hydrologic processes on bedrock detachment, sediment transport, topographic form, and the evolution of the hydrologic processes themselves. Figure 10 shows the proportion of a simulated topography that is saturated for events with different durations and return periods. The two lines show cases where the topography has evolved with and without substantial groundwater flow (the groundwater flow is controlled by changing the saturated hydraulic conductivity). Interestingly, the topography with substantial groundwater flow evolves toward a form that promotes saturated areas particularly for longer duration storms. The same topography also evolves toward a form that promotes runoff, especially from less frequent events (i.e. large return periods). These results hint at a potential feedback loop whereby patterns of runoff production and groundwater discharge modify the topographic surface to enhance their efficiency for certain types of events.

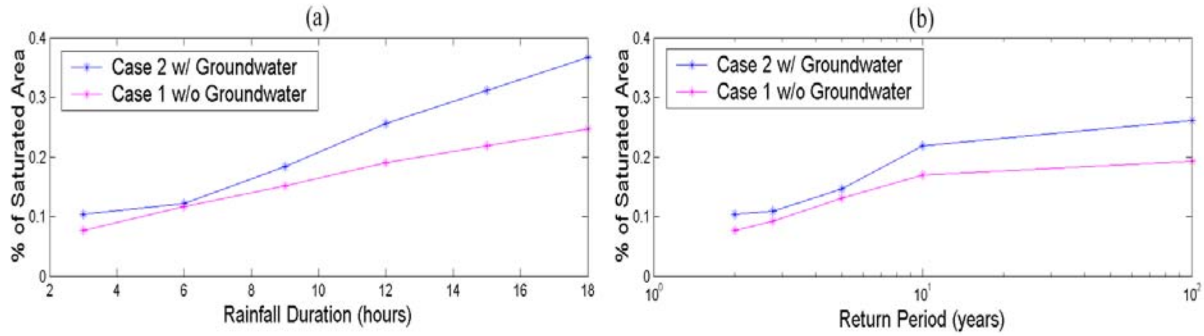

Figure 10. Impact of groundwater runoff on the portion of a basin that saturates during events with different durations (a) and return periods (b)

5 Impacts

A wide variety of Army activities could benefit from soil moisture information at fine spatial and temporal resolutions. For example, soil moisture information can be used to assess the mobility of troops and vehicles during combat, including travel time calculations and optimal travel path determinations. Soil moisture information can also be used to estimate vegetation stem spacing, which impacts mobility. Another activity that depends on soil moisture is land-mine detection. This application would require soil moisture information at very fine resolutions. Land management practices can also benefit from a better understanding of soil moisture patterns and dynamics. For example, the location and timing of training exercises could be selected in part to avoid excessive degradation of training lands.

The research conducted in this project provides an improved base of knowledge that will be used to develop soil moisture interpolation procedures that include the role of topography. Topographic information is available for nearly all regions of the globe at a resolution that is consistent with many Army activities. If topographic information can be quantitatively related to soil moisture patterns in an efficient manner, this information can be used to estimate fine-scale soil moisture patterns from available data. In addition, a better understanding of the relationships between soil moisture and climatic variables such as precipitation and PET provides a better ability to forecast changes in soil moisture with time.

The project will also benefit a range of scientific fields. A new model for regional water balance was presented that can be used to assess the impact of climatic fluctuations and changes on the water cycle of a region. In addition, the new process-based landscape evolution model is expected to have impacts on various geomorphic applications. For example, the model could eventually be used to assess the fate of pollutants on Army lands over long periods of time (when topography must be considered dynamic). Finally, the research conducted in this project is expected to benefit the estimation and simulation of soil moisture for civilian hydrologic applications such as water resources planning and irrigation/agricultural policy development.

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