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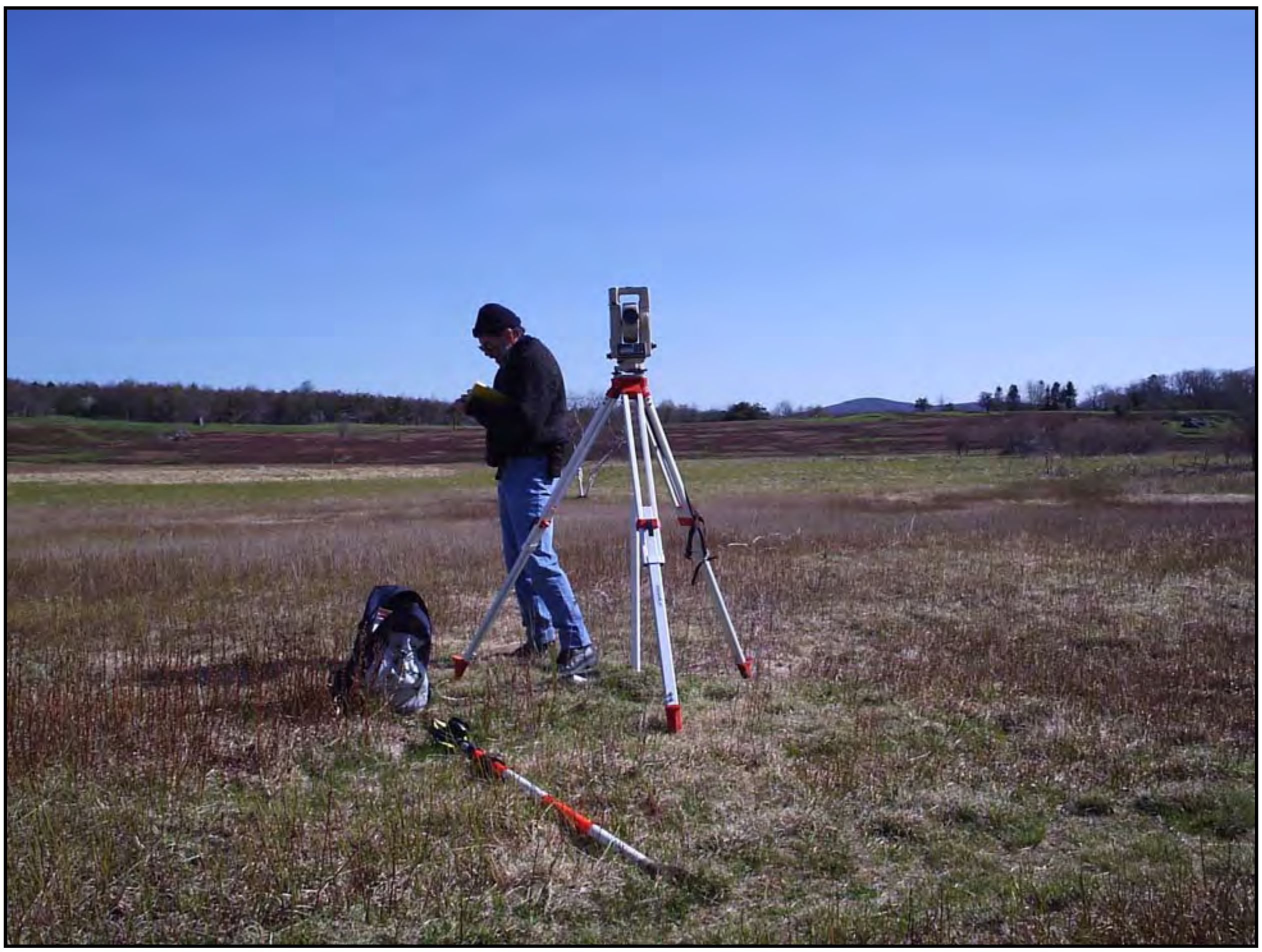
Hydrology of Big Meadows, Shenandoah National Park, Virginia: Assessment of a Sensitive Wetland System in the Blue Ridge Mountains

Technical Report NPS/NER/NRTR—2007/093



ON THE COVER

Measuring elevations of wells at Big Meadows, Shenandoah National Park.
Photograph by Justin E. Lawrence.

Hydrology of Big Meadows, Shenandoah National Park, Virginia: Assessment of a Sensitive Wetland System in the Blue Ridge Mountains

Technical Report NPS/NER/NRTR—2007/093

George M. Hornberger and Justin E. Lawrence[1]

Department of Environmental Sciences
Clark Hall
University of Virginia
Charlottesville, VA 22904

[1]Current Address:
ESPM Ecosystem Sciences Div.,
University of California at Berkeley

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Abstract

The hydrology of Big Meadows is driven by seasonal changes in climate, rainfall and snowfall events, and pumping for water supply. Groundwater levels respond to all of these driving variables. The level of water in the fens at Big Meadows, and therefore their lateral extent in terms of saturated or nearly saturated areas, likewise vary. Knowledge about the variations in moisture levels and groundwater levels across the open meadow and through time can be gained by use of monthly water balance models, both standard climatological water balances and balances estimated by using soil-moisture and groundwater models. The primary data necessary to develop and calibrate such models are meteorological data, soil-moisture data, and data on groundwater levels. The work in this project concentrated on collating existing data, on collecting additional data on soil moisture and groundwater, on analyzing these data, and on synthesizing the data through the use of models. The technical and scientific details of the work, as described in the body of this report, lead to the following inferences that can be useful in planning for water supply and environmental protection at Big Meadows.

(1) The Thornthwaite water balance (TWB), implemented in an Excel spreadsheet, provides a useful summary of monthly climatology for Big Meadows. An important output from the model is moisture surplus (groundwater recharge). A simple time-series (regression) model accurately relates the TWB surplus to discharge at Lewis Spring, which is the primary water-supply source for operations at Big Meadows. Thus, by using seasonal climate forecasts, it would be possible to predict Lewis Spring flows for months into the future. Such scenario forecasts could be useful in planning ahead for the peak summer season.

(2) The backup water supply in cases where flows at Lewis Spring are inadequate to meet demand is currently a well (BM14) about a mile southeast of the Visitors' Center. Use of a well about a third of a mile north of the Visitors' Center was discontinued in the late 1980s when the USGS reported that it was hydraulically connected to the nearby swamp. A critical question is whether use of BM14 might affect water levels in the fen in the southeastern part of Big Meadows. Measured spatial patterns of soil moisture and water levels in shallow wells suggest that the fen is a perched system, vertically separated from the underlying groundwater flow system by unsaturated material and therefore unaffected by groundwater pumping; i.e., pumping from BM14 is unlikely to have an effect on the fen.

(3) Models developed under this project indicate that impacts of future climate change on the hydrology of Big Meadows will lead to more extended areas and periods of low soil moisture, and to lower spatial variability as normally "wet" areas become dry, and to more frequent years of low flow at Lewis Spring. These changes may affect terrestrial ecosystems, especially in the fen in the southeastern meadow, and will certainly affect the reliability of the water supply from Lewis Spring.

Acknowledgments

As co-PIs on the project, Aaron Mills and Jeffrey Sitler provided advice on the project and also oversaw some fieldwork. Their contributions were substantial and are greatly appreciated. The fieldwork was conducted by undergraduate students Quintin Brubaker, Carly Krause, Temple Lee, and Jennifer Pitotti, and by graduate students Justin Lawrence and Lars Nelson. Temple Lee assisted in computations and analyses of the PDSI. Justin Lawrence completed his M.S. degree working on the project; the work on soil-moisture monitoring and modeling is primarily his.

Introduction

Big Meadows is a relatively flat area ~283 ha (~700 ac) at an elevation of some 1,067 m (3,500 ft) containing a rich mosaic of wetland and upland habitats encompassing the only large open area in Shenandoah National Park. An expansive area of Big Meadows lying to the south and east of Skyline Drive has historically been an open meadow. Aerial photographs show that the size of the meadow has declined over the years since the park opened. Currently the meadow is managed to prevent further encroachment of forest by selective removal of shrubs and trees and by controlled burning. The vegetation of the Big Meadows area includes several community types of interest. Two Mafic Fens (types of wetlands) contain globally rare plant communities believed to be endemic to the park and support eight state-rare plant species. The majority of Big Meadows is an Upland Meadow, and two state-rare plants species are found within this community. The Mid-successional Woodland community supports a large population of a state-rare tree. Throughout the meadow, at least 35 plant species have been lost since the mid-1970s. The meadow also supports an abundance of mammals, birds, amphibians, reptiles, and insects, some of which are not found elsewhere in the park. A state-listed snake, a rare insect, and several salamander and bird species are among the animals that occupy the Big Meadows area that are sensitive to changes in hydrology.

The hydrology of the groundwater system underlying Big Meadows is driven by (1) seasonal changes in climate; (2) rainfall and snowfall events; and (3) pumping for water supply. Groundwater levels respond to all of these driving variables. The soil-moisture contents in the fen and surrounding soils, and therefore the lateral extent of the fen in terms of saturated or nearly saturated areas, likewise vary in response to (1) seasonal changes in climate; and (2) rainfall and snowfall events. This study investigates the overall hydrology of Big Meadows and, in particular, the hydrologic connection between the fen and the underlying groundwater flow system and, thus, the potential for groundwater pumping to affect the hydrology of the fen.

The space-time variations in moisture levels and water levels form the knowledge base needed to assist in management of Big Meadows. The best tools for studying management options are monthly water-balance models, both standard climatological water balances and balances estimated by using soil-moisture and groundwater models. The primary data necessary to develop and calibrate such models are meteorological data, soil-moisture data, and data on groundwater levels. The work in this project concentrated on collating existing data, collecting additional data on soil moisture and groundwater, analyzing these data, and synthesizing the data through the use of models.

Water-balance Model

A water balance (Thornthwaite 1948) for Big Meadows was constructed using climatological data from 1943–2002. The water balance is based on the following.

Potential management implications

The water-balance calculation provides estimates of soil-moisture storage and groundwater recharge given monthly measurements (or forecasts) of precipitation and temperature. Calculations updated every month provide a picture of the status of soil and groundwater conditions as they emerge through time. Calculations made on the basis of climate projections for, say, three or six months into the future can then be used to project potential water shortages across the summer season.

1. Monthly Precipitation (inches): This includes all primary sources of water to the surface (rain, snow, sleet, hail, etc). Values were obtained from the National Climate Data Center http://www.ncdc.noaa.gov/oa/ncdc.html.

2. Monthly Precipitation (mm): Precipitation was converted to millimeters for the calculations (conversion of 25.4 mm/1 inch).

3. Average Potential Evapotranspiration (PET): PET is the amount of water that would be evaporated from a continuously wet surface. PET was calculated using the Hamon (1961) method as follows.

   a) Compute e_s, the saturation vapor pressure for each day:
      $e_s = 0.6108\exp[(17.27T)/(237.3+T)]$

   b) Compute H_t, the number of daylight hours on day t:
      $H_t = (24\omega_s)/\pi$, where ω_s is the sunset hour angle of day t:
      $\omega_s = \arccos(-\tan\phi \tan\delta)$, where ϕ is latitude and δ is the solar declination on day J (Julian day) of the year.
      $\delta = 0.4093\sin[(2\pi/365)J-1.405]$
      [Note that all angles are expressed in radians.]

   c) Calculate PET = $[(2.1\, H_t^2\, e_s)/(T+ 273.2)]$
      [We follow Haith and Shoemaker (1987) and set PET = 0 on days for which T is <= 0.]

4. Precipitation – Potential Evapotranspiration (P-PET).

5. Change in Storage (DST): The change in soil-moisture storage is the amount of water that is being added to or removed from storage. The DST falls between 0 and the field capacity.

6. Storage (ST): Storage refers to the amount of soil moisture (water) held in the soil at any particular time. The amount of water depends on soil properties such as soil texture and organic matter content. The maximum amount of water the soil can hold is called the field capacity. Fine grain soils have large field capacities, while coarse grain soils have lower capacities. We assumed a field capacity of 90 mm for Big Meadows.

7. Actual Evapotranspiration (AE): AE is the amount of water delivered to the air from the processes of evaporation and transpiration.

8. Deficit (D): Soil-moisture deficit occurs when AE exceeds the PET, when the demand for water surpasses that which is actually available.

9. Surplus (S): Soil-moisture surplus occurs when P exceeds AE and the soil is at its field capacity. Because it is highly unlikely that there is significant overland flow at Big Meadows, essentially all of the "surplus" is groundwater recharge.

An example of the calculation (Table 1) shows that deficits, when they occur, can be expected mainly in July and August, and that surplus water (groundwater recharge) is available throughout much of the year. In 90% of years, there are no months for which the water balance shows a deficit, but in almost all years the soil moisture is at least partially depleted[1].

Table 1. Water balance for 1964 for a soil-moisture storage of 90 mm, Big Meadows, Shenandoah National Park. All values are mm.

1964	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Monthly Precipitation	126.0	121.2	65.6	157.2	47.8	36.1	83.9	63.8	99.8	96.0	114.0	126.0
Average PET	0.0	0.0	24.6	42.1	73.4	97.9	102.9	82.8	56.8	30.0	21.8	0.0
P-PET	126.0	121.2	41.0	115.1	-25.4	-61.8	-19.0	-19.1	43.0	66.0	92.2	126.0
DST	0.0	0.0	0.0	0.0	-25.4	-61.8	-2.8	0.0	43.0	47.0	0.0	0.0
ST	90.0	90.0	90.0	90.0	64.6	2.8	0.0	0.0	43.0	90.0	90.0	90.0
AE	0.0	0.0	24.6	42.1	73.4	97.9	86.7	63.8	56.8	30.0	21.8	0.0
D	0.0	0.0	0.0	0.0	0.0	0.0	16.2	19.1	0.0	0.0	0.0	0.0
S	126.0	121.2	41.0	115.2	0.0	0.0	0.0	0.0	0.0	19.0	92.2	126.0

[1] All data and models developed under this project are submitted as a separate digital file. The EXCEL spreadsheet for the Thornthwaite water balance includes all 60 years of the analysis.

Palmer Drought Severity Index (PDSI)[2]

Potential Management Implications

The Palmer Drought Severity Index (PDSI) is widely used to indicate drought status. The PDSI for the historical record at Big Meadows was analyzed to examine the distribution of values. The bimodal distribution discovered indicates that one of the common states for Big Meadows is "mild drought". Furthermore, the results show that, according to the PDSI, Big Meadows is under conditions of "moderate drought" or "extreme drought" in over a third of the months of record. This indicates that planning for water use under conditions of limited supply should be the rule rather than the exception for Big Meadows.

One aspect of soil-moisture dynamics that has not been examined in upland wetlands relates to the possibility that there may be preferred states of wetness or dryness. Rodríguez-Iturbe et al. (1991) showed that continental precipitation recycling can lead to distinct steady-state modes of soil-moisture frequency. D'Odorico and Porporato (2004) suggested that soils in Illinois have a strong preference for either dry states or wet states because of a feedback between soil moisture and precipitation. They demonstrated that this bimodality is enhanced during the summer months. Teuling et al. (2005) showed that bimodality in soil moisture can be explained by variations in climate variables without a strong soil moisture-precipitation feedback, and D'Odorico et al. (2000) showed that bimodality can be due to interannual rainfall variability. Spatial distributions of soil moisture can also show bimodality because of fractional precipitation on the area considered (Ryu and Famiglietti 2005). Another possible explanation is that bimodal distributions of summer soil moisture can be due simply to variations in climate from early summer to late summer, without a strong soil moisture-precipitation feedback.

The questions that arise for upland wetlands are (1) are bimodal distributions evident in soil moisture; (2) if so, are they mostly prevalent in the summer season; and (3) if bimodality is evident, is the seasonal variation of climate indicated as a cause?

We investigated soil-moisture dynamics at Big Meadows, VA, using the Palmer Drought Severity Index (PDSI) as a surrogate for soil moisture (because long-term measurements of soil moisture are not available). We examined the frequency distribution of the PDSI for Big Meadows. Details of the analysis procedure are given in Lee and Hornberger (2006).

The analysis can be done including all months, only months from a given season, or only a single month. This is important because bimodality might indicate a tendency for one wet season and one dry, or a tendency for a wet month at the beginning of a season and a dry month at the end of a season. We found that a pronounced bimodality exists for the full year of data and for data from the summer months. Furthermore, our analyses show that the bimodality in the distribution exists for the month of August alone, suggesting that there are intrinsically dry states and wet states and that the bimodality is not merely a result of climate differences from early to late summer (Lee and Hornberger 2006).

[2] The material on the PDSI is taken from Lee and Hornberger (2006)

The PDSI at Big Meadows is at or below -2 for 25.0% of the months in our sixty-year record and is at or below -3 for 11.3% of the time (Figure 1). These values of the index demarcate “moderate” and “severe” drought conditions, respectively. The bimodal nature of the distribution of PDSI suggests that the system has dry conditions as one “preferred state” during the summer. In fact, one of the modes in the distribution of PDSI is around -1, which is the value associated with “mild” drought. The months of July and August are critical months for drought at Big Meadows and our analysis hints that the bimodality in the distribution is not merely due to “wet” Mays and “dry” Augusts, but rather that there are intrinsically dry years and wet years that result in the bimodal distribution.

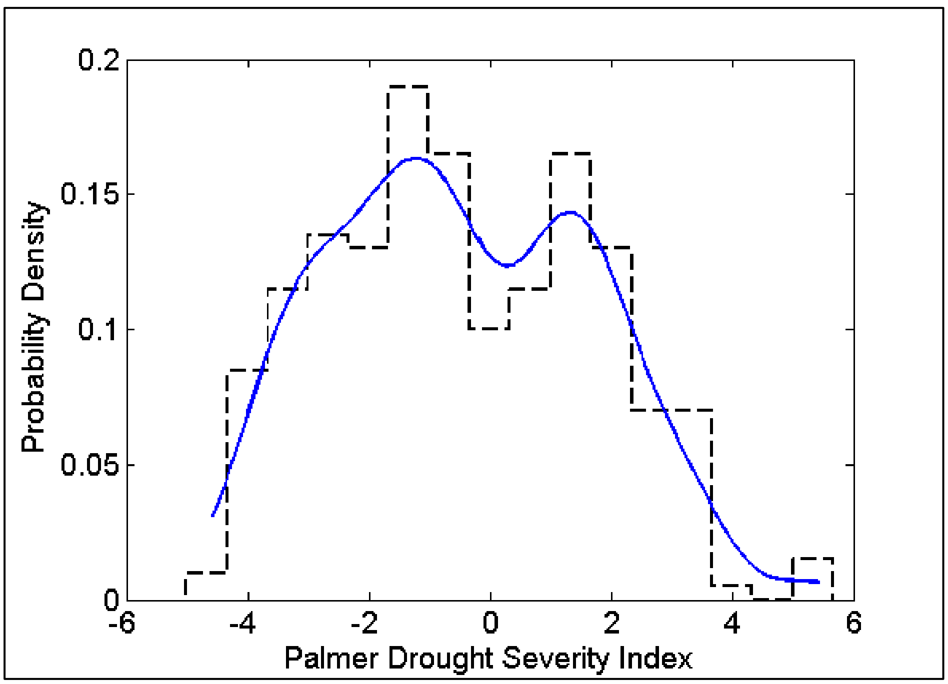

Figure 1. Histogram (dashed line) of monthly values of PDSI (from 1943 to 2002) for Big Meadows, Shenandoah National Park, and a kernel density estimate (solid line) of the distribution.

In June 2005, an array of soil-moisture sampling locations was determined in the open part of Big Meadows across Skyline Drive from the Visitor's Center (Figure 2). Soil moisture was measured across the meadow periodically from June 2005 through May 2007 using a portable time domain reflectometry (TDR) meter (Spectrum® Field Scout TDR 200) with probes 12 cm in length, the estimated depth of the root zone. Locations were recorded using a geographical positioning system (GPS).

Potential Management Implications

Soil-moisture measurements in the fen at Big Meadows provide information on patterns of wetness and how they change seasonally and in response to precipitation. These data may be useful for understanding controls on the distribution of plants and, qualitatively, how future changes in climate might affect the fen. The data are also required to calibrate a soil-moisture model (see following section).

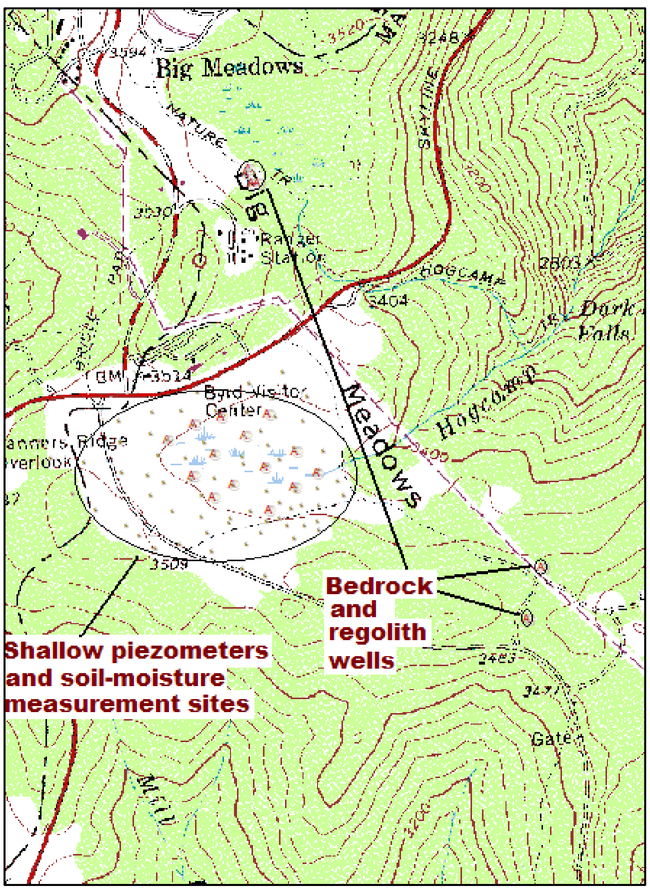

Figure 2. Location map for wells and soil-moisture measurement field within Big Meadows, Shenandoah National Park.

[3] The material on measurement and modeling of soil moisture is taken from Lawrence and Hornberger (2006), Lawrence (2007), and Lawrence and Hornberger (2007).

The spatial patterns of soil moisture (expressed as volumetric water content [VWC]) show a distinct seasonality (Figure 3). On average, the meadow is wettest in winter, when saturated areas (VWC>40%) are present throughout. In spring, the meadow starts to dry and saturated areas become more confined. In summer, the mean moisture reaches lowest levels. In fall, the meadow becomes wet again.

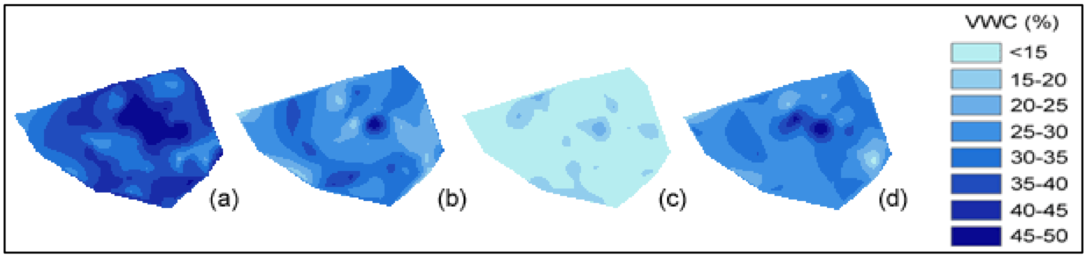

Figure 3. Seasonal patterns of soil moisture expressed as volumetric water content (VWC), June 2005–May 2007, Big Meadows, Shenandoah National Park: (a) winter; (b) spring; (c) summer; and (d) fall.

Patterns were also observed on a storm time-scale (Figure 4). The mean moisture content (VWC) decreased from 41% to 25% over a 5-day period following the storm of 27 Jun 2006. Variance increased by 35% on the first 2 days following the storm and decreased by 36% on days 3 to 5. In general, highest variance tends to be in the middle of dry down periods.

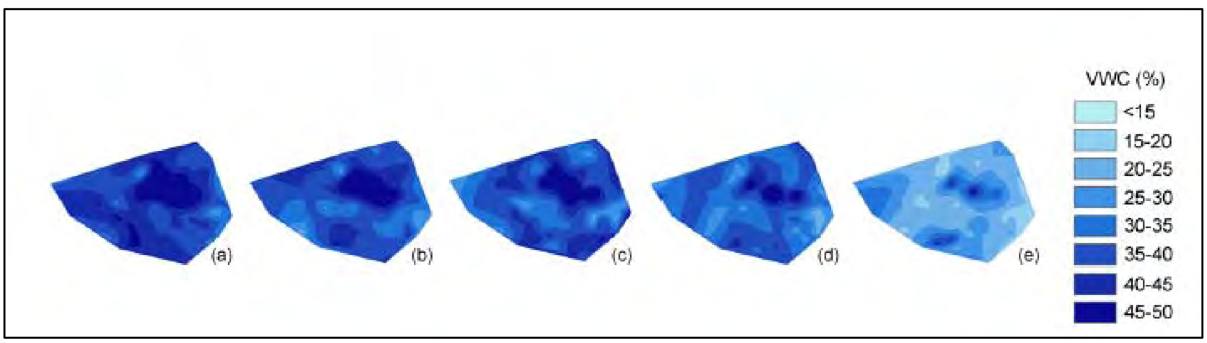

Figure 4. Time-series of soil moisture expressed as volumetric water content (VWC) following the dry down after a storm on 27 June 2006, Big Meadows, Shenandoah National Park: (a) 27 June, 40.8%; (b) 28 June, 38.0%; (c) 30 June, 37.8%; (d) 01 July, 34.7%; and (e) 02 July, 24.8%.

The mean moisture content increased sharply immediately following rainfall events and declined steadily in the days following events. The peak in the mean occurred about 1 day after a rainfall event (Figure 5) and the peak in variance occurred after about 3–4 days (Figure 6). Although mean and variance peaked at different times, they followed the same general pattern of an increase after events followed by a decrease.

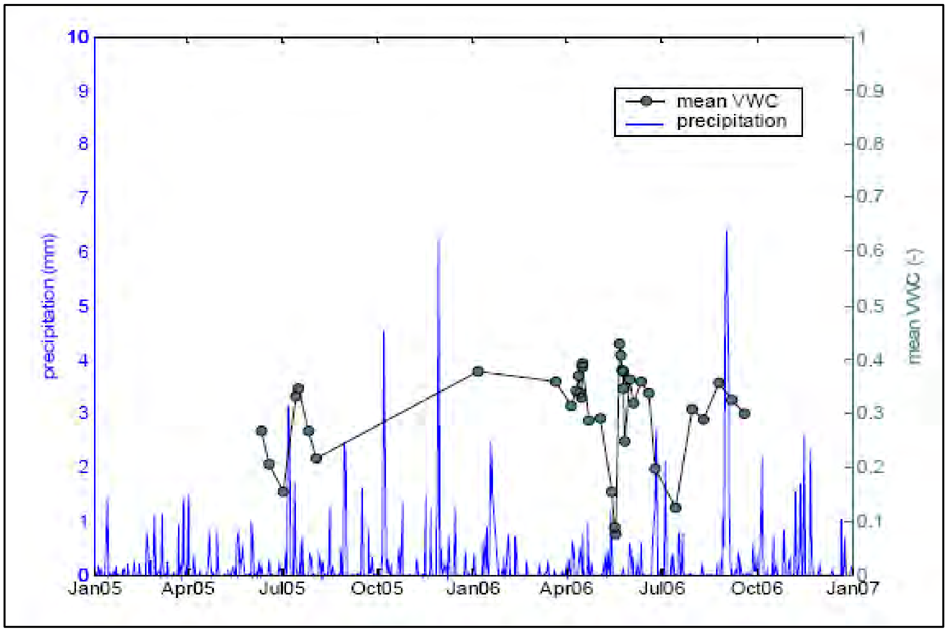

Figure 5. Observed mean soil moisture expressed as volumetric water content (VWC) and precipitation, Big Meadows, Shenandoah National Park.

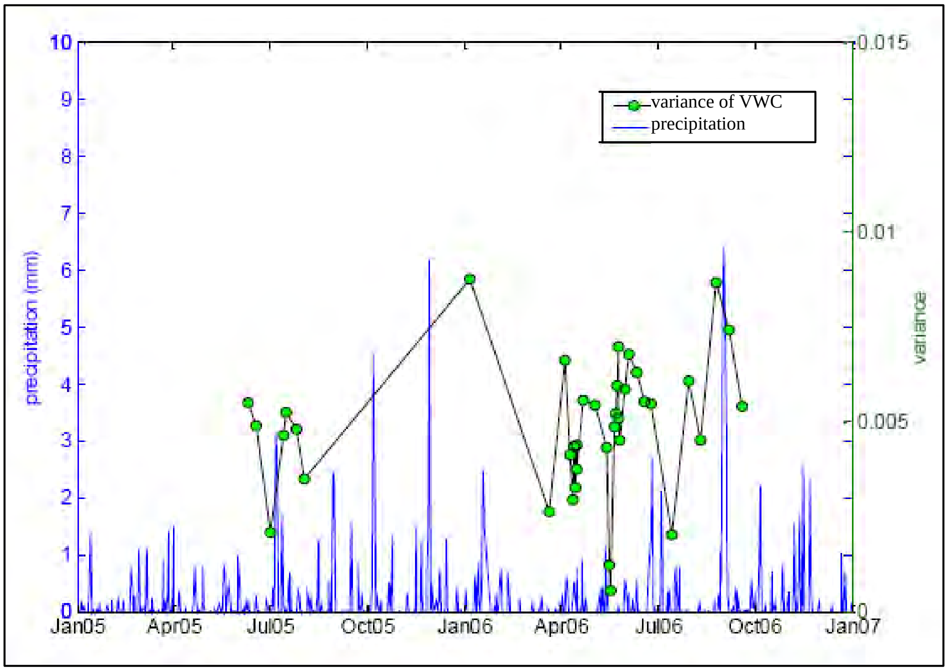

Figure 6. Observed variance of soil moisture expressed as volumetric water content (VWC) and precipitation, Big Meadows, Shenandoah National Park.

Distinct trends in the spatial moisture pattern were observed under different wetness conditions (Figure 7). Even in the driest times, two wet areas were present near the middle of the meadow. As the meadow soils got wetter, the extent of these two areas increased. Once the wetness reached about 35%, the two wet areas merged into one large area. The soil with high moisture content was well confined to this large area until the average reached about 40%, at which point more wet areas began appearing in the south.

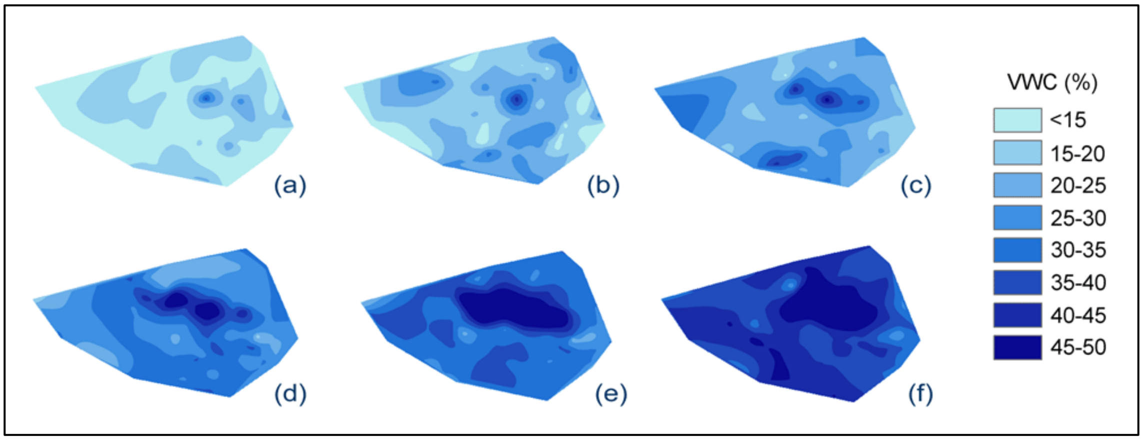

Figure 7. Exemplar soil-moisture patterns expressed as volumetric water content (VWC) as a function of wetness for (a) 15%, (b) 20%, (c) 25%, (d) 35%, (e) 40%, and (f) 45% moisture content (nearest-neighbor interpolation), June 2005–May 2007, Big Meadows, Shenandoah National Park.

The percent of the observation points contained in different moisture ranges was plotted against the mean moisture contents to quantify the portion of the total area in different ranges under different wetness conditions (Figure 8). The decline in the 0%–20% moisture range as the meadow got wetter is a sigmoid curve because the distribution is bounded on the low end by the field capacity. As the meadow gets wetter, the soil fills the 20%–30% and 40%–50% ranges. These mid-moisture content curves are bell shaped because they are assumed random distributions, not bounded by soil properties. As the wetness approaches the porosity (saturation), an increasing portion fills the 40%–50% and 50%–60% ranges. The distribution in these high ranges has a long lower tail, bounded on the upper end by the porosity.

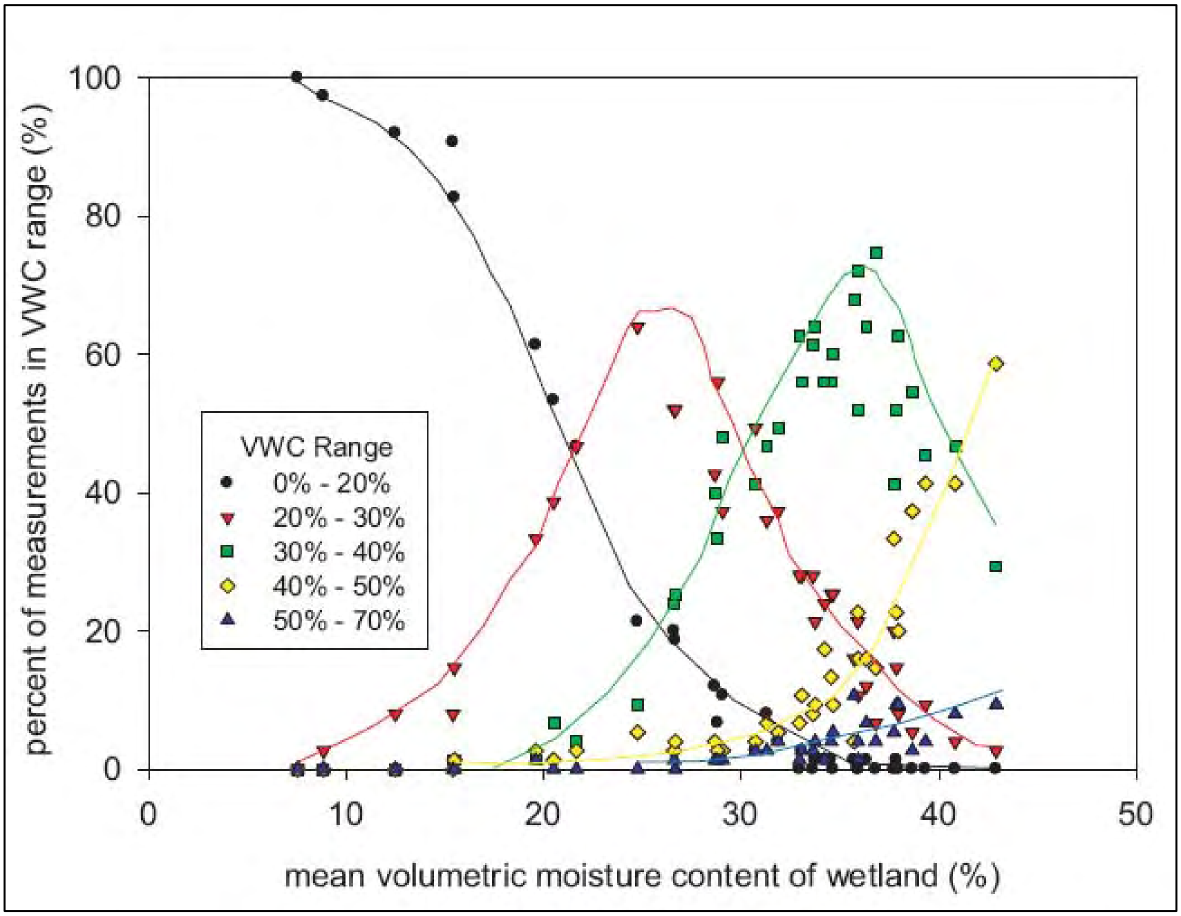

Figure 8. Percentage of total observation area in different soil-moisture ranges (expressed as volumetric water content [VWC]) for specific mean volumetric moisture contents, derived from field observations between June 2005 and May 2007, Big Meadows, Shenandoah National Park.

Teuling and Troch (2005) developed a soil-moisture dynamics model that accounts for variations in soil properties by specifying probability density functions and using Monte-Carlo simulation. They applied the model at three catchments in different environments, and successfully reproduced some of the main features of observed soil-moisture variability. We modified this model for Big Meadows to use land-surface variables derived from field data.

Potential Management Implications

The soil-moisture model makes it possible to understand what controls the variance in soil moisture in the fen. The model can also be used to estimate how soil-moisture levels and variance would change given scenarios of climate change or vegetation change.

Soil Hydraulic Conductivity

Soil hydraulic conductivity, k, was measured at the 75 soil-moisture measurement points (Figure 2) with a mini-disk infiltrometer under 2 cm suction; k was calculated from the cumulative infiltration curve using the method proposed by Zhang (1997), in which a quadratic expression is fit to a cumulative infiltration vs. time plot. The hydraulic conductivity equals C_1, the coefficient of the x^2 term, divided by A, a value that relates the van Genutchen parameters of a particular soil type to the suction rate and the disk radius.

The value of A, 8.1, was computed from the van Genutchen parameters – n and α (Carsel and Parrish 1998), the radius of the infiltrometer disk (r_0, 2.2 cm), and the suction at the disk surface, (h_0, 2 cm). The equation is

$$A = \frac{11.65\left(n^{0.1}-1\right)\exp[2.92(n-1.9)\alpha h_0]}{(\alpha r_0)^{0.91}} \qquad n \geq 1.9 \qquad (1)$$

$$A = \frac{11.65\left(n^{0.1}-1\right)\exp[7.5(n-1.9)\alpha h_0]}{(\alpha r_0)^{0.91}} \qquad n < 1.9 \qquad (2)$$

For one data set, C_1 is equal to 0.028; the hydraulic conductivity of the soil is 0.0035 cm s^{-1} (Figure 9). The hydraulic conductivity was computed in this way for each of the observation points.

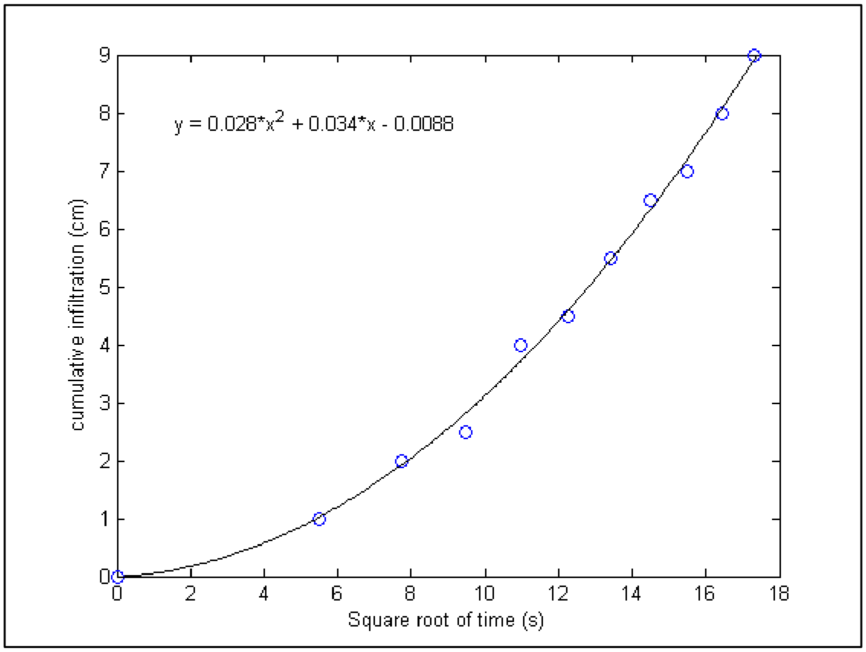

Figure 9. Example quadratic equation from the infiltration curve.

Slope and Aspect

A 7.5'×7.5' USGS Digital Elevation Model (DEM) was obtained from the Geospatial and Statistical Data Center in Alderman Library at the University of Virginia. A DEM is an array of ground elevations sampled at regularly spaced intervals that represents cartographic information in raster form. The 7.5'×7.5' DEM corresponds with the USGS 1:24,500 topographic quadrangle and has 10m×10m spacing with the Universal Transverse Mercator (UTM) projection.

A layer was made in ESRI® ArcInfo 9.1 for the DEM and for the 75 observation points. The *aspect* and *slope* functions in the ArcInfo toolbox were used to determine the topographic characteristics (Figure 10). The slope raster shows the maximum change in elevation over the distance between a cell and its eight neighbors. Aspect, the compass direction a hill faces, is the steepest down slope direction from each cell to its neighbors.

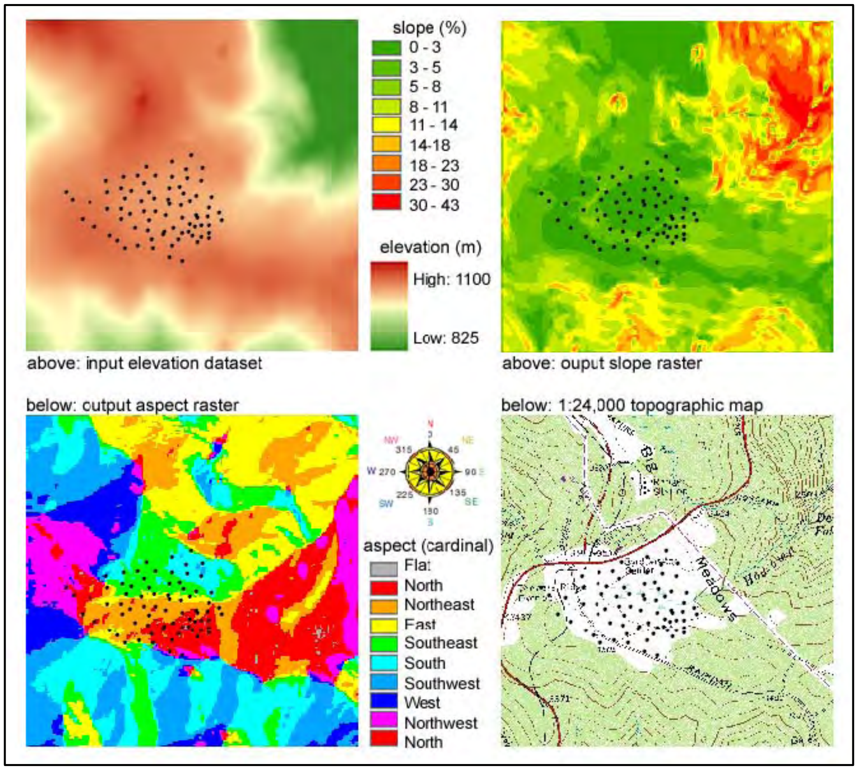

Figure 10. Topographic characteristics at the soil-moisture observation sites (black dots) in Big Meadows, Shenandoah National Park.

Soil Texture Analysis

The particle size distribution of soil samples from the shallow wells was determined; one sample was from 30 cm below the surface, one sample was from 45 cm below the surface, and one sample was from 55 cm below the surface. Soil texture was classified by mechanical analysis, whereby the ratio of clay, sand, and silt in the samples was determined and matched with a given soil type in the textural pyramid.

Atmospheric conditions

Precipitation data for Big Meadows are available beginning in 1997 from the National Park Service (NPS) meteorological station[4]. Four rain gages were installed to test if precipitation is spatially uniform. The rain gauges were operated only a few weeks, just to examine variability relative to the NPS station report. Variability was small, so we conclude that use of the NPS station record for the entire meadow is appropriate.

[4] http://ard-aq-request.air-resource.com/

Soil-moisture Model

The Teuling and Troch (2005) model was adapted to use land-surface variables derived from field data and thereby describe observed spatio-temporal patterns. The model inputs included critical moisture content (θ_c), leaf area index (LAI), precipitation, potential evapotranspiration (E_p), porosity (ϕ), and wilting point (θ_w). It was driven with hourly data for periods of one year.

The necessary assumptions were (1) negligible lateral flow in the root zone, (2) negligible bare soil evaporation compared to evapotranspiration from vegetation, and (3) spatially uniform precipitation. For Big Meadows, the shallow slope of the land surface justified the first assumption and dense vegetation cover justified the second assumption.

The basic Teuling and Troch (2005) model is given by the following equations

Soil-moisture balance
$$\frac{d\theta_v}{dt} = \frac{1}{L}(T - R - q - S) \quad (3)$$

T = throughfall [L/T]
R = saturation excess runoff [L/T]
q = deep drainage [L/T]
S = root water uptake [L/T]

Deep Drainage
$$q = k_s \left(\frac{\theta}{\phi}\right)^{2b+3} \quad (4)$$

k_s = saturated hydraulic conductivity
b = a pore size distribution parameter

Root water uptake
$$S = f_r \beta \left[1 - \exp(-c * LAI)\right] E_p \quad (5)$$

f_r = root fraction in the layer of depth L
β = a soil-moisture stress function
c = a light use efficiency parameter
LAI = leaf area index

Soil-moisture stress
$$\beta = \max\left[0; \min\left(1; \frac{\theta - \theta_w}{\theta_c - \theta_w}\right)\right] \quad (6)$$

Land-cover
$$LAI = LAI_{\max}\left[c_1 - (1 - c_1)\sin\left(2\pi \frac{DOY - c_2}{c_3} + \frac{\pi}{2}\right)\right] \quad (7)$$

LAI_{max} = local maximum of leaf area index
c1,c2,c3 = parameters that specify the seasonal development of LAI

Hourly precipitation and temperature time-series data came from the NPS station. Ep was calculated with the Hamon (1961) formula. All other parameters (Table 2) were fitted from observations or adapted from Teuling and Troch (2005). LAImax was taken as the value Teuling and Troch (2005) used for the VCR-LTER site at the eastern shore of Virginia.

To account for topography, Ep was multiplied by a slope factor, Sf , which is the ratio of radiation received on a sloped surface to the radiation received on a flat surface. Sf was calculated using a method described by Dingman (2002) that employs the concept of equivalent slope developed by Lee (1964). The basic idea is that the angle of incidence of radiation on a sloping plane at latitude Λ and longitude Ω is the same as the angle of incidence on an equivalent horizontal plane many degrees longitude removed from the plane.

Table 2. Soil-moisture model parameters.

Parameter	Value
θ_w [-]	0.15ϕ[a]
θ_c [-]	0.45ϕ[a]
μ_k,σ_ξ [-]	3.6,0.5[b]
c	0.55[b]
f_r	0.8[b]
c1,c2,c3 [-,d,d]	0.5,114,260[b]
ε [-]	0.01[a]

[a] fitted from observations
[b] adapted from Tueling and Troch (2005)

Model Results

The adapted Teuling and Troch (2005) model captured the relationship between total variance and the mean moisture content (Figure 11). The variance was controlled by the wilting point under low moisture conditions and by the porosity under high moisture conditions. Because the model tended to show a bias and an over-prediction of variance, some adjustments of the model results were necessary to bring them into conformance with the observed soil-moisture patterns. The porosity was adjusted by increasing the observed soil-moisture from the day after a large storm by 25%, and multiplying by a scaling factor of 5. The wilting point was set to equal the porosity multiplied by 0.15. With these simple adjustments, the model fit the observations reasonably well.

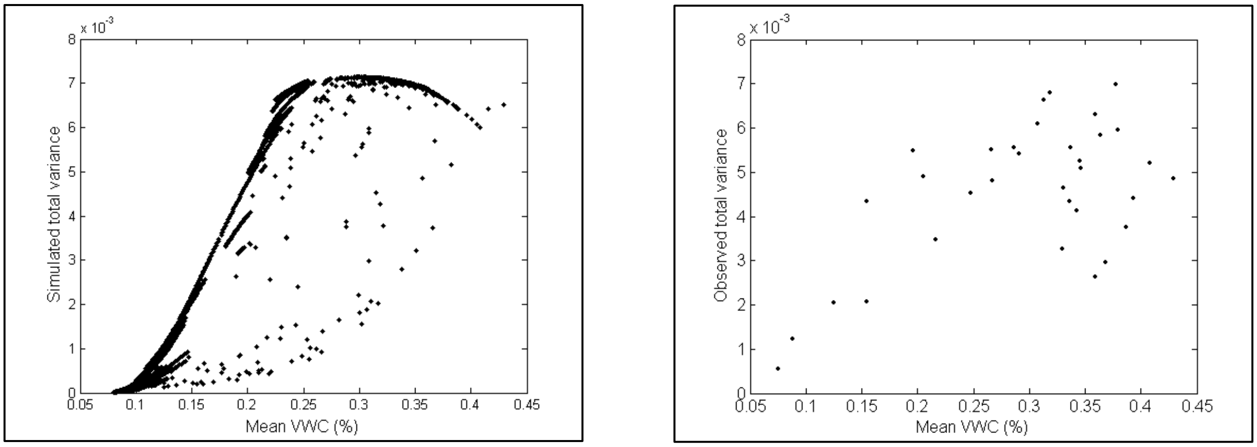

Figure 11. Simulated and observed total variance vs. mean soil moisture expressed as volumetric water content (VWC).

Variance in soil moisture at Big Meadows peaked at intermediate moisture contents (Figure 12), a pattern that can be compared to smoothed patterns at other sites described by Brocca et al. (2007). The examples were chosen to be illustrative of different climate zones, but clearly they do not represent all possible patterns because variability depends on factors other than climate.

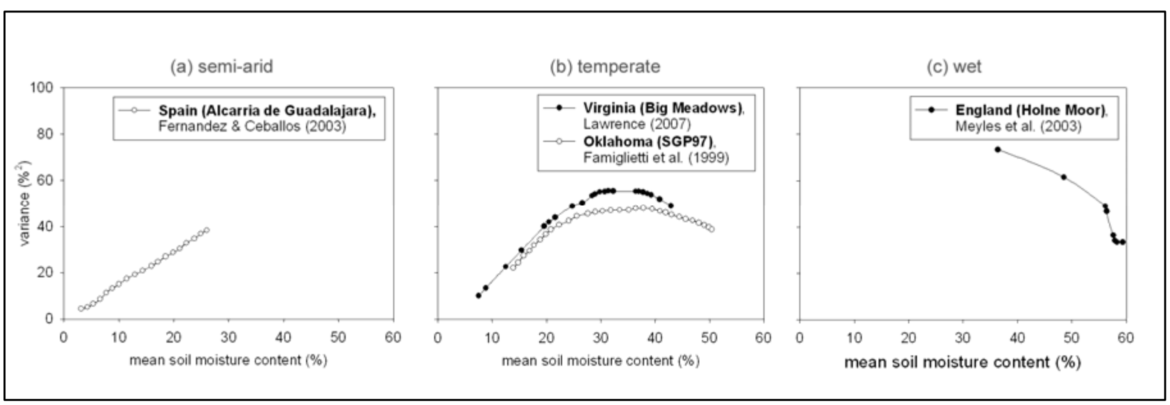

Figure 12. Smoothed relationship between mean soil-moisture content and variance from studies on soil-moisture variability in (a) semi-arid, (b) temperate, and (c) wet regions.

The model can be used to explore the controls of variance by increasing and decreasing the variance in the wilting point, soil conductivity, and porosity while holding the means of these variables constant. At low mean soil-moisture, variance is controlled by the wilting point (Figure 13a); more variance in the wilting point gives more variance in soil-moisture. At intermediate mean soil-moisture, variance is controlled by the soil conductivity (Figure 13b);

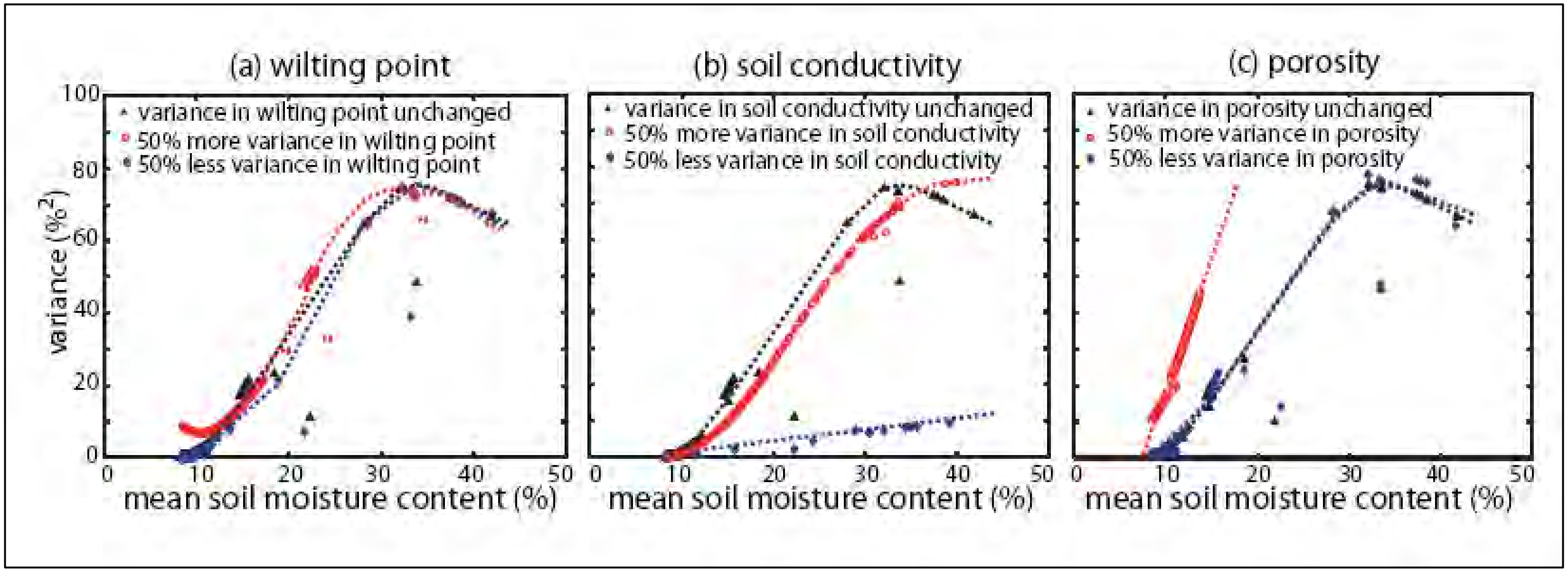

Figure 13. Modeled response to variability in wilting point, soil conductivity, and porosity.

less variance in soil conductivity gives less variance in soil-moisture. At high mean soil-moisture, variance is controlled by the porosity (Figure 13c); more variance in the porosity gives more variance in soil-moisture.

The magnitude of variance in soil-moisture is predominately controlled by the wilting point at low mean soil-moisture contents, by the soil conductivity at intermediate soil-moisture contents, and by the porosity at high soil-moisture contents (Figure 13). In semi-arid regions, heterogeneity in vegetation effectively influences soil-moisture variability because vegetation is related strongly to the wilting point. In temperate regions, heterogeneity of topography effectively influences soil-moisture variability because soil conductivities are related strongly to the soil-moisture content; soils tend to be wetter at the bottom of slopes and on slopes facing north or east. In wet regions, heterogeneity of soil types effectively influences soil-moisture variability because porosities are related strongly to the soil texture.

The model is structured such that it reflects plant processes (e.g., see equations for root-water uptake and land cover). Thus, it provides a tool that can be used to explore scenarios in which plant type changes in the fen. The model could be used to explore the potential effects of different management schemes for the vegetation cover at Big Meadows, for example.

Groundwater Measurements

In the summer of 2004 two shallow piezometers were placed near the middle of the meadow approximately 200 m (656 ft) apart. They both reach depths of about 2.5 m (8 ft), which was a meter below the water table at the time of emplacement in June. Two more wells were established; then the presence of abundant cobbles, which occur as float in the soil throughout most of the meadow, made normal construction of the remainder of the wells impossible. A permit amendment was obtained to allow a larger diameter hole for easier emplacement of well piping. Because of this, an archeological survey was then required at each site. Throughout September 2004, Carol Nash and her team of archeologists from James Madison University examined material that was dug from twelve additional sites, for a total of sixteen well locations in varying degrees of completion (Figure 2)

> Potential Management Implications
>
> Groundwater measurements in the fen show that drainage is toward Hogcamp Branch. This flow pattern is consistent with the concept that shallow ground water in the fen is perched above the regional water table. A major implication is that pumping from well BM14, the well identified as a backup water supply for the Visitors' Center, is unlikely to have any significant effect on water in the fen.

Installation of shallow monitoring wells was completed in summer of 2005, with 14 of the 16 wells constructed. Because the graduate student leading this effort withdrew from the program at this time, the measurements of water levels lagged. A new graduate student started on the project in November 2005 and water-level monitoring was begun at that time. Surveying to establish elevations of all wells was completed in the fall of 2006.

Well hydrographs indicate water levels in shallow piezometers vary substantially and quickly in response to rainfall events; whereas, deeper wells respond much more slowly (Figure 14). Well BM14 (nomenclature of Martin 2002) is available as a pumping well for auxiliary supply when flow at Lewis Spring is insufficient. One question that arises is whether pumping might affect the hydrology in the meadow south of Skyline Drive. Our results suggest that the water in the fen is perched[5] above the water table in this area and is not hydraulically connected with the underlying groundwater system. Not only are there rapid temporal variations in head, which are not mimicked in BM9 (Figure 15), but also the spatial pattern indicates a local drainage system feeding the ephemeral stream that becomes Hogcamp Branch (Figure 16). The water table elevation at Well BM9 is consistently about 1,053 m (3,454 ft). The water table elevation at Well BMW2 ranges from about 1,056–1,057 m (3,464–3,467 ft), approximately 4–5 m (10–15 ft) higher than at BM9. If the water levels measured by the shallow piezometer system and BM9 were all part of the same regional water table, then we would expect the water level in BM9 to be higher than the fen, as ground water would be flowing toward the natural discharge area along Hogcamp Branch. Spatial patterns for other measurement dates are similar (Figure 17). [Note

[5] Perched Water--a localized zone of water that sits on a relatively impervious material that restricts vertical flow. A perched zone is typically at a higher elevation than the regional aquifer system with unsaturated conditions below it. (Adapted from: http://www.if.uidaho.edu/~johnson/ifiwrri/sr3/gloss.html)

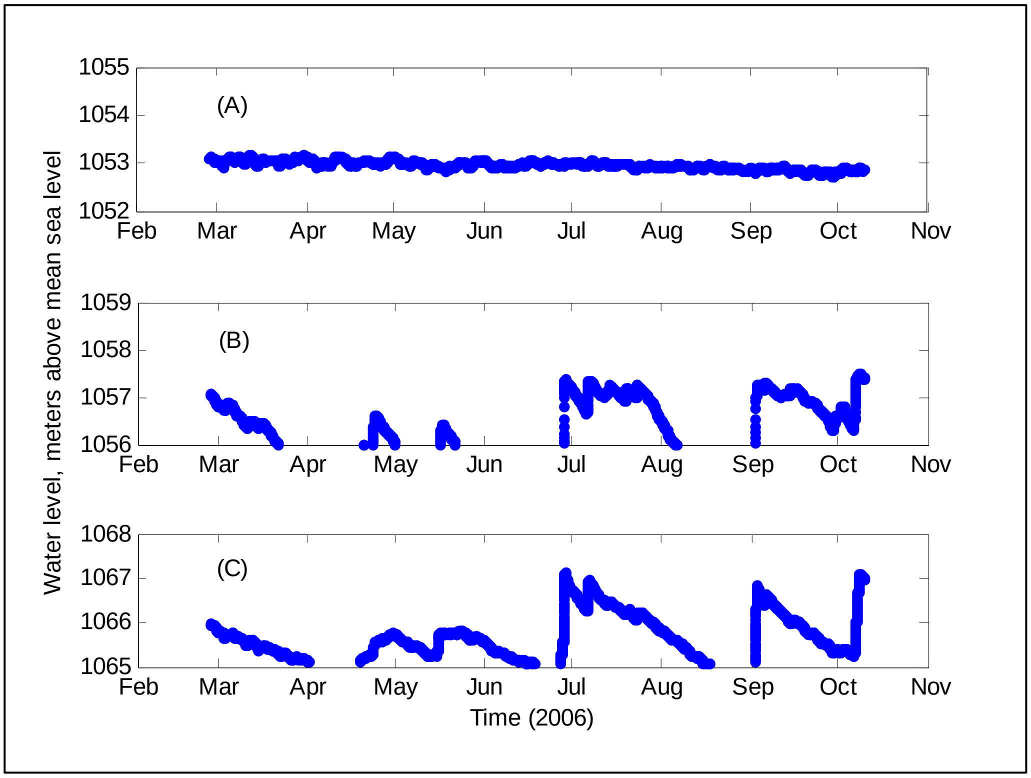

Figure 14. Recorded water levels in wells at Big Meadows, Shenandoah National Park: (A) well BM9, 107 m depth; (B) piezometer BMW2, 2.5 m depth. (C) well 43 S14, 16.7 m depth. When no data are indicated, the wells were dry.

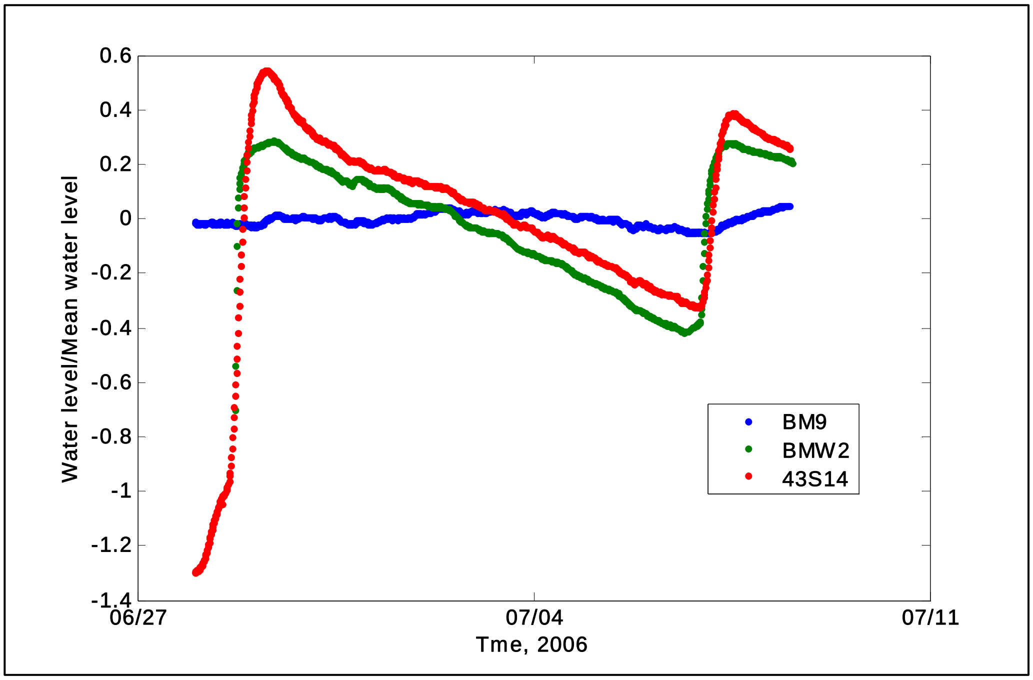

Figure 15. Relative water level changes in three wells during summer 2006, Big Meadows, Shenandoah National Park.

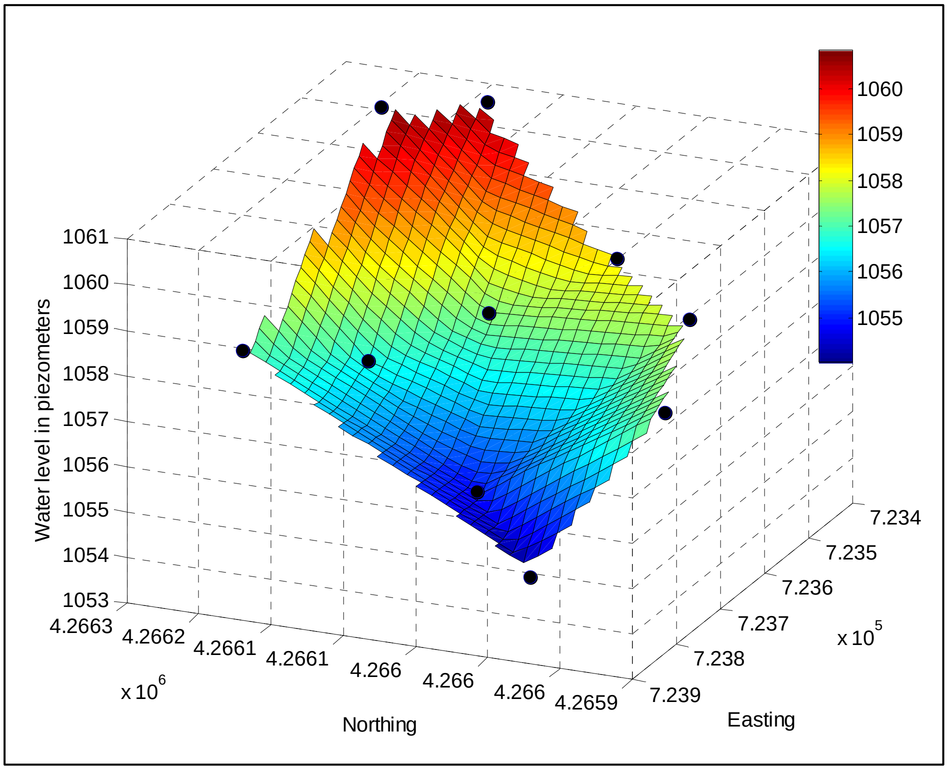

Figure 16. Water levels in the piezometer field in December 2006, Big Meadows, Shenandoah National Park. The head gradients imply that the water is draining to the low point at Hogcamp Branch.

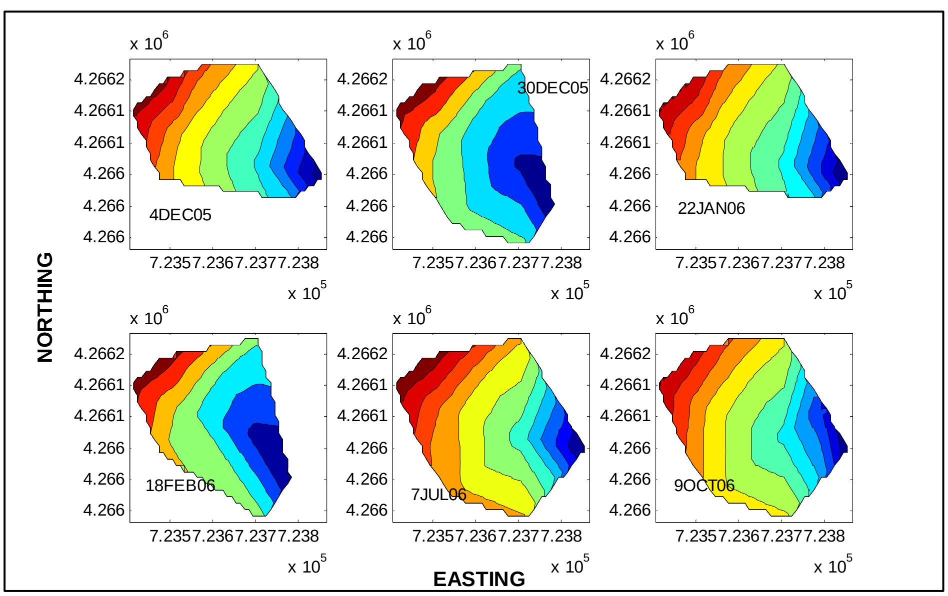

Figure 17. Patterns of water table elevations for the shallow piezometer system, Big Meadows, Shenandoah National Park. Absolute values of the levels indicated by the colors differ for each time period but the pattern shows that the direction of groundwater movement is toward Hogcamp Branch in each case.

that contour plots for the piezometers were done only for days when there were fewer than six of the piezometers with no water.] Results using a numerical model (see following section) support the concept that the water table in the fen is perched above the regional water table.

The student version of VISUAL MODFLOW was used to examine features of the groundwater system at Big Meadows (a copy of the program is distributed with the book by Fetter 2001). A digital elevation model (DEM) was used as a base map for the system (Figure 18). Following Martin (2002), we took the 1,000 m contour (approximately equal to the 3,400 ft contour of Martin) to define the areal extent of the Big Meadows system. We set discharge points at Lewis Spring, Davids Spring, two branches of Hogcamp Branch, Dark Hollow, Mill Prong, and E. Branch Naked Creek. We set a constant head at these boundaries. We took average recharge to be 658 mm/year from the Thornthwaite model. We "calibrated" the model by trying to match the measured (average) groundwater levels at wells 43 S6 and 43 S7 (nomenclature of Lynch 1987) and at BM9.

Potential Management Implications

Groundwater modeling is useful for exploring water-level relationships with discharge from springs and creeks. It is also possible to use the model to explore potential effects of pumping on the aquifer. Results from the model support the interpretation that the fen is perched, adding additional circumstantial evidence to the conclusion that pumping from BM14 is unlikely to cause adverse effects in the fen.

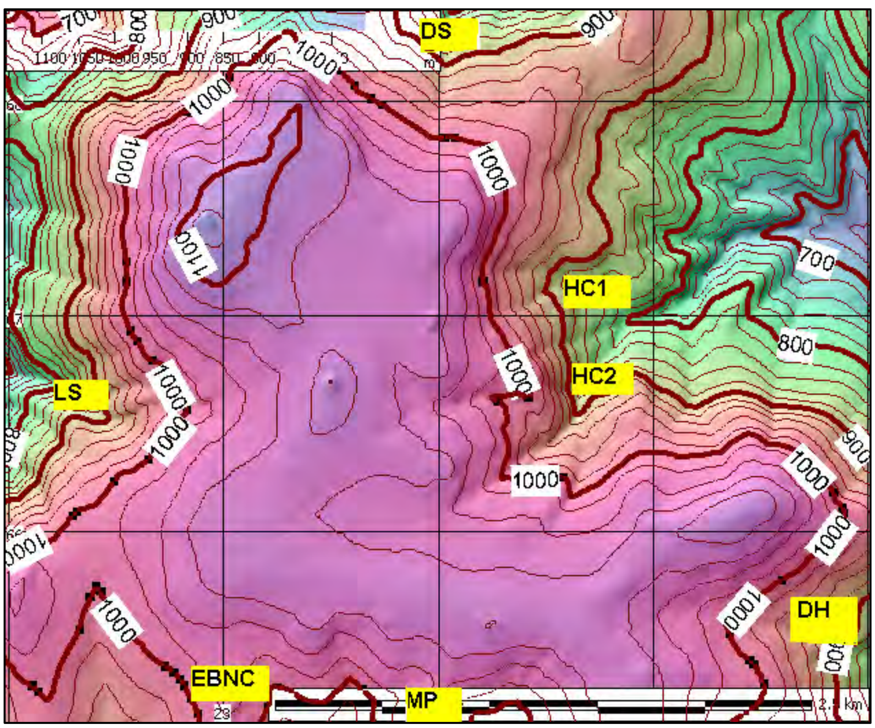

Figure 18. Base map for the groundwater system, Big Meadows, Shenandoah National Park. Elevation contour lines (meters) are in maroon. The map colors reflect elevations, e.g., the 800-m contour lies in the green background and the highest elevations (>1100 m) lie in the blue-grey background. LS=Lewis Spring; DS=Davids Spring; HC1 and HC2 = Hogcamp Branch; DH=Dark Hollow; MP=Mill Prong; EBNC=East Branch Naked Creek.

To get a sensible simulation, we used small regions of high hydraulic conductivity near the discharge points. The results for groundwater heads of the steady-state simulation give reasonable values (Figure 19). The calculated heads at the three wells are within about 2 m (6.5 ft) of observed values. Note, however, that the simulated level of the regional water-table at the location of BMW2, the shallow piezometer where we installed a continuous level recorder, is more than 10 m (32.8 ft) below the measured values in the piezometer (when water is observed in the piezometer). This supports the notion that the water in the meadow is perched above the perennial water table. The contours of groundwater head (Figure 20) indicate that the recharge area feeding Lewis Spring is larger than that defined by the topographic contours (cf. Figure 3 in Martin 2002) but a good bit smaller than the entire area bounded by the 1,000-m (3,400-ft) contour. Although this model can be considered only a crude approximation, one can begin to appreciate what a reasonable extent of the capture zone for Lewis Spring might be (Figure 20), a consideration that has significant practical use (see Martin 2002).

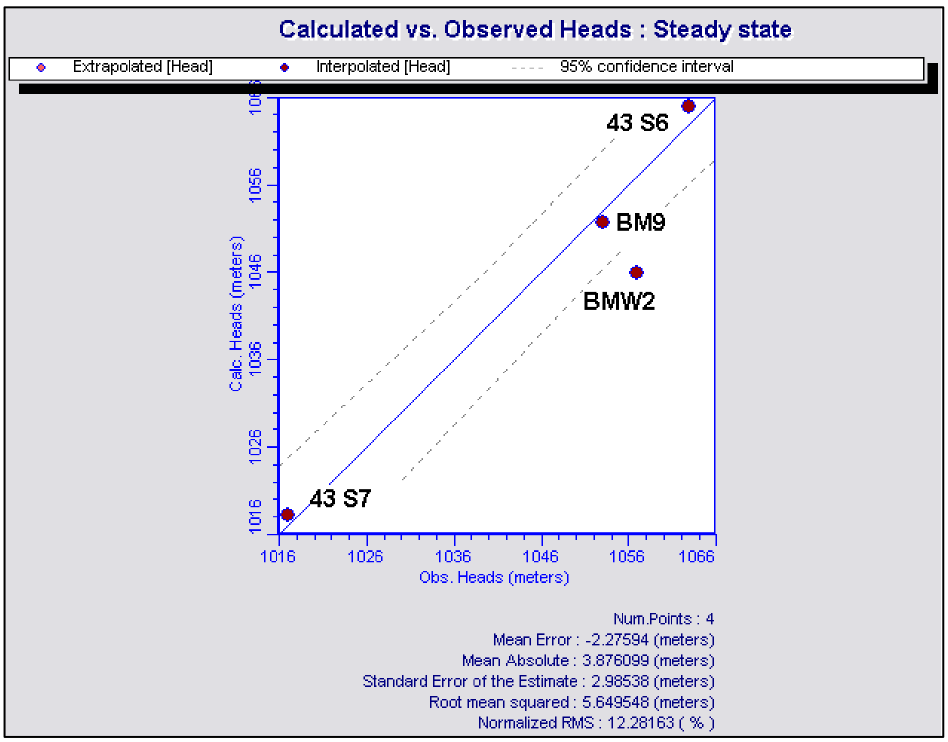

Figure 19. Simulated and observed groundwater heads, Big Meadows, Shenandoah National Park.

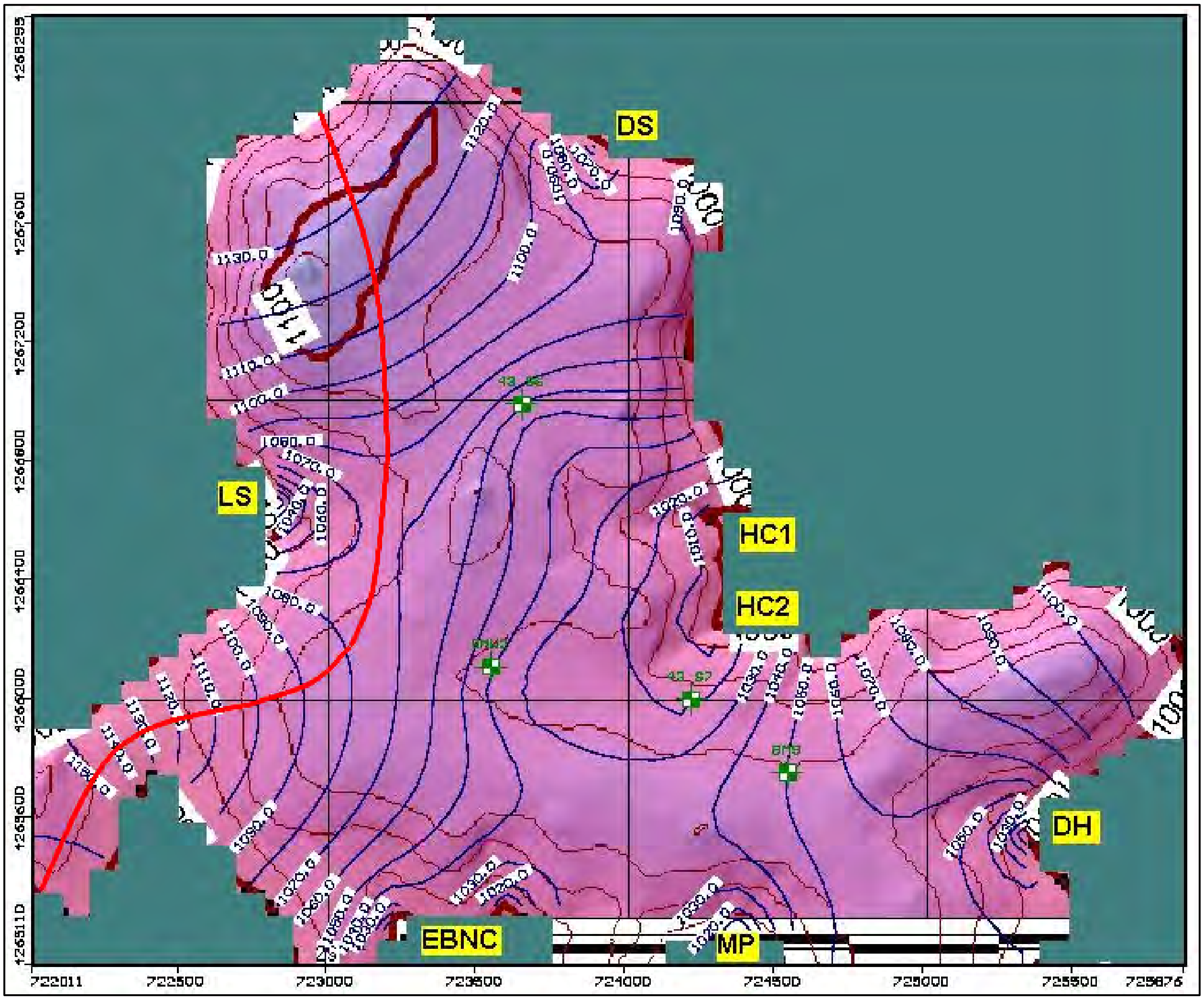

Figure 20. Contours (meters) of simulated steady-state groundwater head for the regional water table at Big Meadows (blue), Shenandoah National Park, without pumping from wells. The maroon lines are surface contours and the map background colors reflect surface elevations as for Figure 18. Discharge points are Lewis Spring (LS), Davids Spring (DS), Hogcamp Branch (HC1 and HC2), Dark Hollow (DH), Mill Prong (MP), and East Branch Naked Creek (EBNC). The red line indicates the approximate extent of the capture zone for Lewis Spring on the basis of the simulation.

Statistical Analyses of Flows at Lewis Spring

A key piece of information needed for water management at Big Meadows is the discharge at Lewis Spring, a major source of water for the site. Continuous flow records for the spring are not available, so direct statistical analyses are not possible. We developed a surrogate time series of Lewis-Spring discharges using our long-term water balance. Sporadic measurements of discharge at Lewis Spring are available for 1960 to1970 (DeKay 1972), and include a three-year period where continuous (monthly) discharge measurements are available. We used the measurements for these years to calibrate a time-series model relating the surplus water calculated from the water balance (as described previously in the Water-balance Model section) to the discharge at Lewis Spring.

> Potential Management Implications
>
> Statistical analyses of low flows are a standard tool for planning. A time series model to relate recharge calculated using the water balance approach (see the section on Water Balance above) to sporadic measurements of discharge at Lewis Spring, the main water supply for the Visitors' Center, allows creation of a synthetic long-term record of flows. Subsequent low-flow frequency analysis allows estimates of probabilities of supply shortages. For example, the results indicate that for one year in four (25% probability), the low monthly flow will be less than or equal to about 45 gpm. Such information is of direct relevance for long-term planning.

$$\hat{Q}(t_j) = 0.7004Q(t_{j-1}) + 0.7155S(t_j) \qquad (8)$$

where $\hat{Q}(t_j)$ is the estimate of discharge at Lewis Spring in month *j* in million gallons, $Q(t_{j-1})$ is the (measured or estimated) discharge for the previous month, and $S(t_j)$ is the computed surplus from the water balance for month *j* in mm. The time constant for this model is about three months, which is consistent with the young ages for Lewis Spring found by Plummer et al. (2000).

When the model is run as a one-step-ahead prediction, i.e., when it is updated with a measurement of discharge at the spring when available in the record presented by DeKay (1972), the results are quite good (Figure 21). Even when the model is run as a straight prediction, i.e., it is started with an initial value for $Q(t_{j-1})$, but afterward the $Q(t_{j-1})$ on the right side of equation (8) is replaced by the estimated value, $\hat{Q}(t_{j-1})$, the results for low values of flow are represented reasonably well (Figure 22).

The water-balance results for the entire period of record can be used to generate a synthetic record of discharge at Lewis Spring for 60 years and, again, the low flows appear to be simulated reasonably well (Figure 23).

A primary advantage of having the synthetic record is that low-flow statistics can be computed. For each year of 60 years in the record, the minimum monthly discharge is selected to create an annual series. A lognormal distribution fits these data reasonably well (Figure 24).

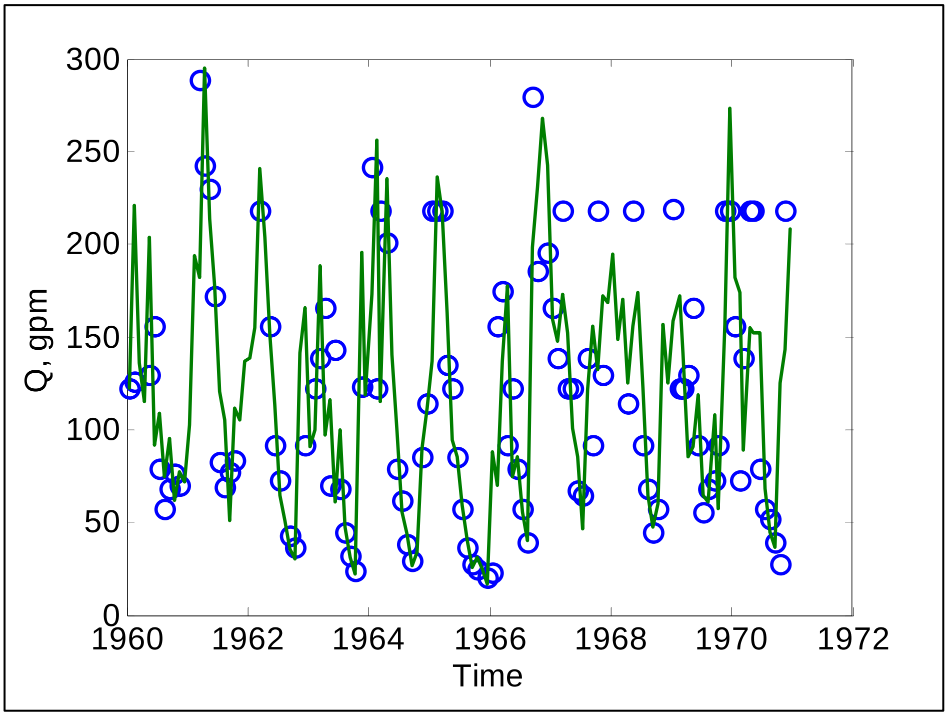

Figure 21. One-step-ahead prediction of spring discharge (line) and flows measured by DeKay (1972) at Lewis Spring, Big Meadows, Shenandoah National Park.

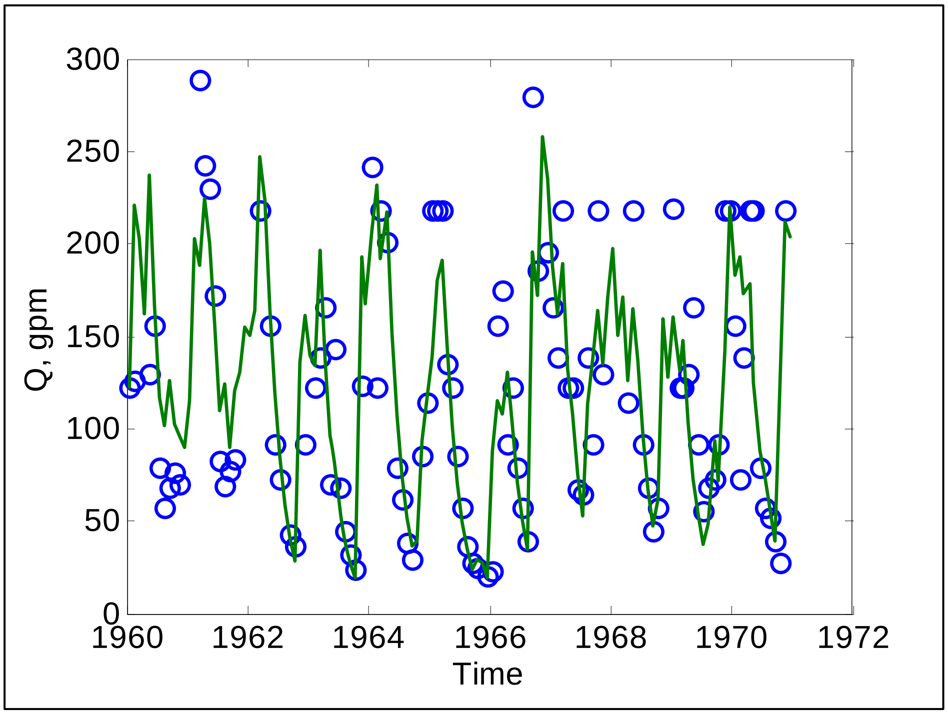

Figure 22. Time-series model prediction (line) with no updating and measured discharge at Lewis Spring, Big Meadows, Shenandoah National Park.

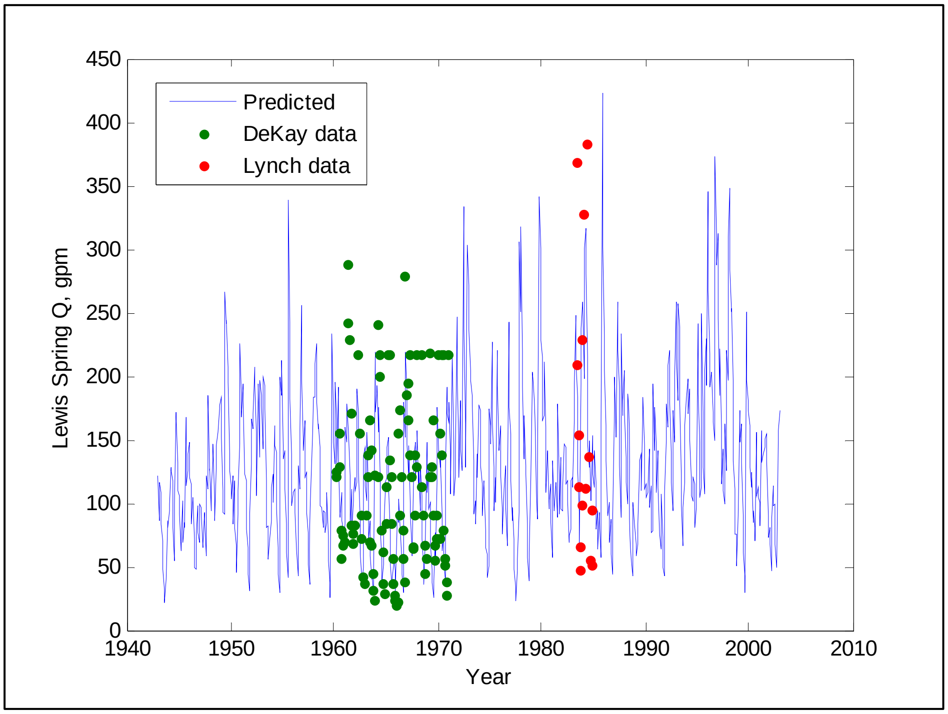

Figure 23. Synthetic record of discharge at Lewis Spring, Big Meadows, Shenandoah National Park, developed using the time-series model.

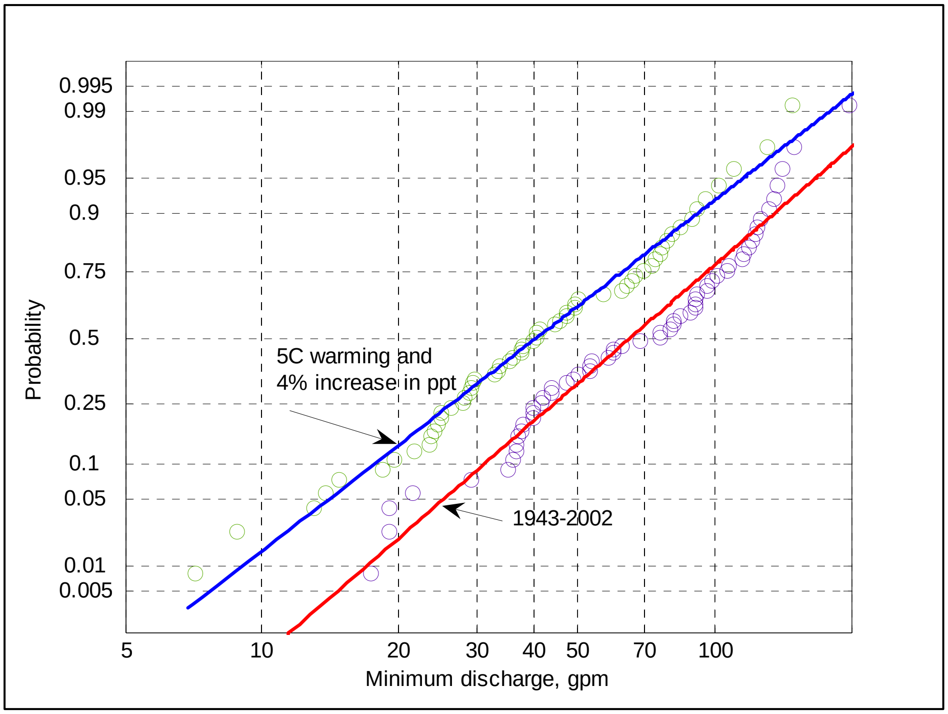

Figure 24. Probability plot for discharge of Lewis Spring, Big Meadows, Shenandoah National Park, showing effects of hypothetical climate change.

Projections of climate change in the mid-Atlantic under greenhouse gas warming scenarios mainly show increased temperature and slight increases in precipitation. Over the last 100 years, precipitation in the United States increased about 4% (Groisman and Easterling 1994). General-circulation models forecast that increased CO_2 in the atmosphere will cause global temperature to rise about 5°C in the next 100 years (Kaufmann and Stern 1997). The rise in temperature would produce an increase in evapotranspiration rates and the amount of water vapor in the atmosphere, and thereby increase precipitation by 3% to 15% (Loaiciga et al. 1996).

Detailed seasonal projections for temperature change and precipitation are highly uncertain. Although seasonal changes are likely to be important (e.g., most projections show summer precipitation increasing and winter precipitation relatively unchanged), we illustrate potential changes using the simple approach of applying a uniform 5°C temperature increase and a uniform 4% increase in precipitation. The computation is meant to be illustrative and not to represent expected changes precisely. The changes were applied to the 60-year record of temperature and precipitation, and the water balance for the scenario was computed using the Thornthwaite method. The calculated surplus was then used in equation (8) to create a synthetic record of discharge at Lewis Spring for the climate-change scenario. The result is a marked change in the low-flow frequency (Figure 24).

Conclusions

(1) The Thornthwaite water balance (TWB) provides a useful summary of climatology for Big Meadows.

(2) The TWB shows that there is no soil-moisture deficit at the meadow in about 9 out of 10 years.

(3) The surplus calculated from the TWB is an estimate of groundwater recharge and can be used to predict flows at Lewis Spring.

(4) An analysis of the Palmer Drought Severity Index shows that Big Meadows has intrinsically "dry" states and "wet" states (Lee and Hornberger 2006).

(5) Soil-moisture patterns in the meadow change seasonally and in response to storms. Wet areas at the lower elevations tend to be persistent except in very dry periods (Lawrence 2007).

(6) Variance in moisture content is highest at intermediate mean moisture contents (Lawrence 2007; Lawrence and Hornberger 2007).

(7) Under climate change, dry periods in the meadow southeast of the Visitors' Center are expected to become more prevalent in late summer (Lawrence 2007).

(8) Water levels in shallow piezometers respond rapidly to rainfall events; levels decline rapidly in an extended dry period.

(9) Measured spatial patterns of soil moisture and water levels in shallow wells suggest that the fen is a perched system, vertically separated from the underlying groundwater flow system by unsaturated material and therefore unaffected by groundwater pumping; i.e., pumping from BM14 is unlikely to have an effect on the fen. Results from a groundwater model also support this interpretation.

(10) The discharge at Lewis Spring can be modeled accurately using the surplus from the TWB as input. Given short-term (monthly to seasonal) climate forecasts, the model may be useful for planning water supply at Big Meadows.

References

Brocca, L., R. Morbidelli, F. Melone, and T. Moramarco. 2007. Soil moisture spatial variability in experimental areas of central Italy. Journal of Hydrology 333:356–373.

Carsel, R. F., and R. S. Parrish. 1998. Development of joint probability distributions of soil water retention characteristics. Water Resources Research 24:755–769.

DeKay, R. H. 1972. Development of groundwater supplies in Shenandoah National Park, Virginia. Mineral Resources Report 10, Virginia Division of Mineral Resources. 158 pp.

Dingman, S. L. 2002. Physical hydrology. Prentice Hall. Upper Saddle River, NJ.

D'Odorico, P., and A. Porporato. 2004. Preferential states in soil moisture and climate dynamics. Proceedings of the National Academy of Sciences 10:8848–8851.

D'Odorico P., L. Ridolfi, A. Porporato, and I. Rodríguez-Iturbe. 2000. Preferential states of seasonal soil moisture: the impact of climate fluctuations. Water Resources Research 36:2209–2219.

Famiglietti, J. S., J. A. Devereaux, C. A. Laymon, T. Tsegaye, P. R. Houser, T. J. Jackson, S. T. Graham, M. Rodell, and P. J. van Oevelen. 1999. Ground-based investigation of soil moisture variability within remote sensing footprints during the Southern Great Plains 1997 (SGP97) Hydrology Experiment. Water Resources Research 35:1839–1851.

Fernandez, J. M. and A. Ceballos. 2003. Temporal stability of soil moisture in a large-field experiment in Spain. Soil Science Society of America Journal 67:1647–1656.

Fetter, C.W. 2001. Applied Hydrogeology. Prentice Hall. Upper Saddle River, NJ.

Groisman, P. Ya., and D. R. Easterling. 1994. Variability and trends of total precipitation and snowfall over the United States and Canada. Journal of Climate 7:184–205.

Hamon, W. R. 1961. Estimating potential evapotranspiration. Journal of the Hydraulic Division 87:107–120.

Haith, D. A., and L. L. Shoemaker. 1987. Generalized watershed loading functions for stream flow nutrients. Water Resources Bulletin 23:471–478.

Kaufmann, R. K., and D. I. Stern. 1997. Evidence for human influence on climate from hemispheric temperature relations. Nature 388:39–44.

Lawrence, J. E. 2007. Soil-Moisture Variability at Big Meadows, Shenandoah National Park, Virginia: Impacts on the Water Balance. Master's Thesis. Department of Environmental Sciences, University of Virginia.

Lawrence, J. E., and G. M. Hornberger. 2006. Soil Moisture Variability and Critical Moisture Levels at Big Meadows, Shenandoah National Park, Virginia. Eos Trans. AGU 87(52). Fall Meet. Suppl. Abstract H13A–1346.

Lawrence, J. E., and G. M. Hornberger. 2007. Soil-moisture variability across climate zones. Geophys. Res. Lett. 34: L20402, doi:10.1029/2007GL031382..

Lee, R. 1964. Potential insolation as a topoclimatic characteristic of drainage basins. International Association of Scientific Hydrology Bulletin 9:27–41.

Lee, T. R., and G. M. Hornberger. 2006. Inferred bimodality in the distribution of soil moisture at Big Meadows, Shenandoah National Park, Virginia. Geophys. Res. Lett. 33 L06407 doi:10.1029/2005GL025536.

Loaiciga, H. A., et al. 1996. Global warming and the hydrologic cycle. Journal of Hydrology 174:83–127.

Lynch, D. D. 1987. Hydrologic Conditions and Trends in Shenandoah National Park, Virginia, 1983–84. U. S. Geological Survey. Water-Resources Investigations Report 87-4131. Richmond, VA. 115 pp.

Martin, L. 2002. Drinking Water Source Protection Plan, Big Meadows Area, Shenandoah National Park. NPS-Water Resources Division. Ft. Collins, CO. 17 pp.

Meyles, E., A. Williams, L. Ternan, and J. Dowd. 2003. Runoff generation in relation to soil moisture patterns in a small Dartmoor catchment, Southwest England. Hydrological Processes 17: 251–264.

Plummer, L. N., et al. 2000. Chemical and isotopic composition of water from springs, wells, and streams in parts of Shenandoah National Park, Virginia and vicinity, 1995–1999. USGS Open-file report 00-373. 70 pp.

Rodríguez-Iturbe, I., D. Entekhabi, and R. Bras. 1991. Nonlinear dynamics of soil moisture at climate scales: 1. Stochastic analysis. Water Resources Research 27:1899–1906.

Ryu, D., and J. S. Famiglietti. 2005. Characterization of footprint-scale surface soil moisture variability using Gaussian and beta distribution functions during the Southern Great Plains 1997 (SGP97) hydrology experiment. Water Resources Research 41. W12433. 10.1029/2004WR003835.

Teuling, A. J., R. Uijlenhoet, and P. A. Troch. 2005. On bimodality in warm season soil moisture observations. Geophysical Research Letters 32, L13402, doi:10.1029/2005GL023223.

Teuling, A. J., and P. A. Troch. 2005. Improved understanding of soil moisture variability dynamics. Geophys. Res. Lett. 32, L05404, doi:10.1029/2004GL021935.

Thornthwaite, C. W. 1948. An approach toward a rational classification of climate. Geogr. Rev. 38:55–94,

Zhang, R. 1997. Determination of soil sorptivity and hydraulic conductivity from the disk infiltrometer. Soil Sci. Soc. Am. J. 61:1024–1030.

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Northeast Region
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