MODELING SOIL WATER VARIABILITY

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Abstract

This report demonstrates the process of simulating the temporal and spatial variability of soil water. We use a highly instrumented catchment in Texas for this demonstration. We use a one-dimensional water budget model, based on equations from the SWRRB model to demonstrate time variability of soil moisture at a point. We also demonstrate methods of interpolating the spatial patterns of soil water with various semi-variogram and kriging techniques. These methods help us analyze the spatial structure of point measurements and predictions (such as those by SWBM) of soil water status. In combination, these methods are demonstrated to be useful tools for examining the soil water under various environmental conditions and therefore could be used to study the effects of land-cover and land-use changes on water resources.

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INTRODUCTION

Soil water is a key element in determining the amount and location of runoff. Land cover changes and land-use practices alter the patterns of soil water and therefore runoff and water available for plant growth. In planning changes in the cover and use of the surface it is helpful to consider tools of simulation to evaluate the effects of changes beforehand.

This report demonstrates two methods of soil water simulation with example applications of soil water balance models and spatial variability models. Some of the background of these models is presented in this report and additional details are found in Nieber and Lopez Bakovic (1987). The first section presents the details of example applications of some of the models used for simulating the soil water balance at a point. The second section presents some examples of soil water spatial variability modeling.

MODELING OF SOIL WATER AT A POINT

We first present the details of example applications of some of the models used for simulating the soil water balance at a point. Three illustrations are given. The first illustration is the generation of synthetic daily weather data by the model WGEN (Richardson and Wright,1984). The second and third illustrations are derived from the application of the Soil Water Balance Model (SWBM) to the simulation of the daily soil water balance at a point and to the estimation of effective precipitation at a given location.

Synthesis of daily weather data demonstration

In the analysis, design, and operation of modern water resources systems it is common to simulate the hydrologic processes involved using mathematical models of those processes. Output from these models might include variables such as soil water content, evapotranspiration, sediment yield, and streamflow. The output might be for a single rainstorm event or for a long-term sequence (on the order of tens of years) of events.

A major input to these mathematical models is the weather data including precipitation and evapotranspiration related information. At most locations the weather records are not sufficiently long to meet the requirements of a specific hydrologic study. Consequently it is frequently necessary to use synthetically generated weather data which mimic the characteristics of the observed climatic conditions at a specific location.

One method for synthesizing weather records is that presented by Richardson (1981) and incorporated into the model WGEN (a model for generating daily weather variables). WGEN generates daily records of precipitation, maximum temperature, minimum temperature, and solar radiation for any selected length of time and for any location. The model operates by first generating a value of precipitation for a given day and then generates the other variables based on whether the day is wet or dry. Thus the correlation between precipitation occurrence and the other weather variables is preserved in the generated data. The value of precipitation is generated based on a Markov chain procedure so that the time dependence in precipitation is preserved.

The input to WGEN include the following:

1) Probabilities for the transition from wet days to dry days and for wet days to wet days. These transition probabilities are a function of the time of year and are given as monthly values.

2) Parameters in the gamma distribution function for rainfall amount. These parameters are a function of the time of year and are given as monthly values.

3) Mean and amplitude of the seasonal harmonic describing the time-dependent variation of the mean and standard deviation of the maximum daily temperature, minimum daily temperature, and daily solar radiation. These means and amplitudes need to be given each for the conditions of wet days and dry days.

To illustrate the use of WGEN a one year record of daily weather variables was synthesized for the location of Minneapolis, Minnesota. The generated weather variables of precipitation, maximum and minimum air temperature, and solar radiation are plotted in Figure 1. The seasonal pattern in the temperatures and the daily solar radiation, and the random variations about the seasonal pattern in these variables are demonstrated clearly in the illustrations.

Daily soil water balance at a point

The balance of soil water in the soil profile at a point can be expressed by the equation

$$d(S) = I + U - ET - DP - LF \qquad (1)$$

where I is infiltration, ET is evapotranspiration, DP is deep percolation, LF is lateral flow, S is soil water stored, and d( ) refers to the change in the quantity included in the parentheses. In performing the calculation of a soil water balance the variables in equation (1) are calculated using equations based on either empirical relationships or the physics of water flow in soils.

A soil water balance model (SWBM) was developed to solve equation (1) with the assumption that lateral flow (LF) is equal to zero. The variables in equation (1) were calculated using equations employed in the model referred to as "Simulator of Water Resources for Rural Basins (SWRRB)" and described by Williams et al. (1985). The SWBM is less comprehensive than the SWRRB because it does not simulate overland flow, streamflow, lateral flow, or soil erosion as in SWRRB.

The inputs to the SWBM include the following:

1) Daily rainfall, solar radiation, and maximum and minimum air temperature. This data can be generated by the synthetic weather data generator WGEN.

2) Characteristics of the soil layers composing the soil profile. These characteristics include the thickness of the soil layers, the field capacity and wilting point of the soil layers, the saturated hydraulic conductivity of the soil

layers, the Soil Conservation Service (SCS) runoff curve number for the soil layers, the time-dependent pattern of root distribution in the soil layers, and the time-dependent distribution of leaf-area index for the crop growing on the soil.

To illustrate the application of the SWBM the Minneapolis location used in the WGEN demonstration was used. The daily weather variables for one year were generated with WGEN and this information was input to the SWBM. The soil conditions selected as input corresponded to conditions for a loamy clay soil. The simulation was performed for the period April 1 through October 31 since the SWBM does not currently consider frozen soil conditions. The soil water profile was assumed to be at field capacity on April 1.

The results of the SWBM simulation are plotted in Figures 2a to 2d. The simulated rainfall is given in Figure 2a. Of the rainfall events shown there are none that are greater than 2 inches. However, there are a few periods where closely spaced storms occur.

The daily runoff amount is illustrated in Figure 2b and daily soil water is presented in Figure 2d. The daily soil water is presented both according to the amount stored in each layer as well as the total amount stored in the soil profile. It should be observed that runoff from the simulated rainfall events tends to reflect the soil water amount at the time of the rainstorm events. For example, the total soil water content in the top two soil layers began to decrease significantly at about day 175. On day 175 a rainfall of 24 mm occurred and this produced a runoff of 11 mm. The total soil water in the top two layers on day 175 is 115 mm. In contrast, on day 200 a rainfall of 22 mm produced a runoff of 6 mm. The total soil water in the top two layers on day 200 is 45 mm. The results demonstrate that a drier antecedent moisture condition produces a smaller runoff amount.

The daily evapotranspiration is plotted in Figure 2c. This plot reflects the seasonal variation in daily ET. The influence of increased daily ET on stored soil water during the peak of the growing season is clearly illustrated in comparing Figures 2c and 2d. Daily ET begins to increase substantially following day 175 and corresponding to this time is the substantial decrease in stored soil water.

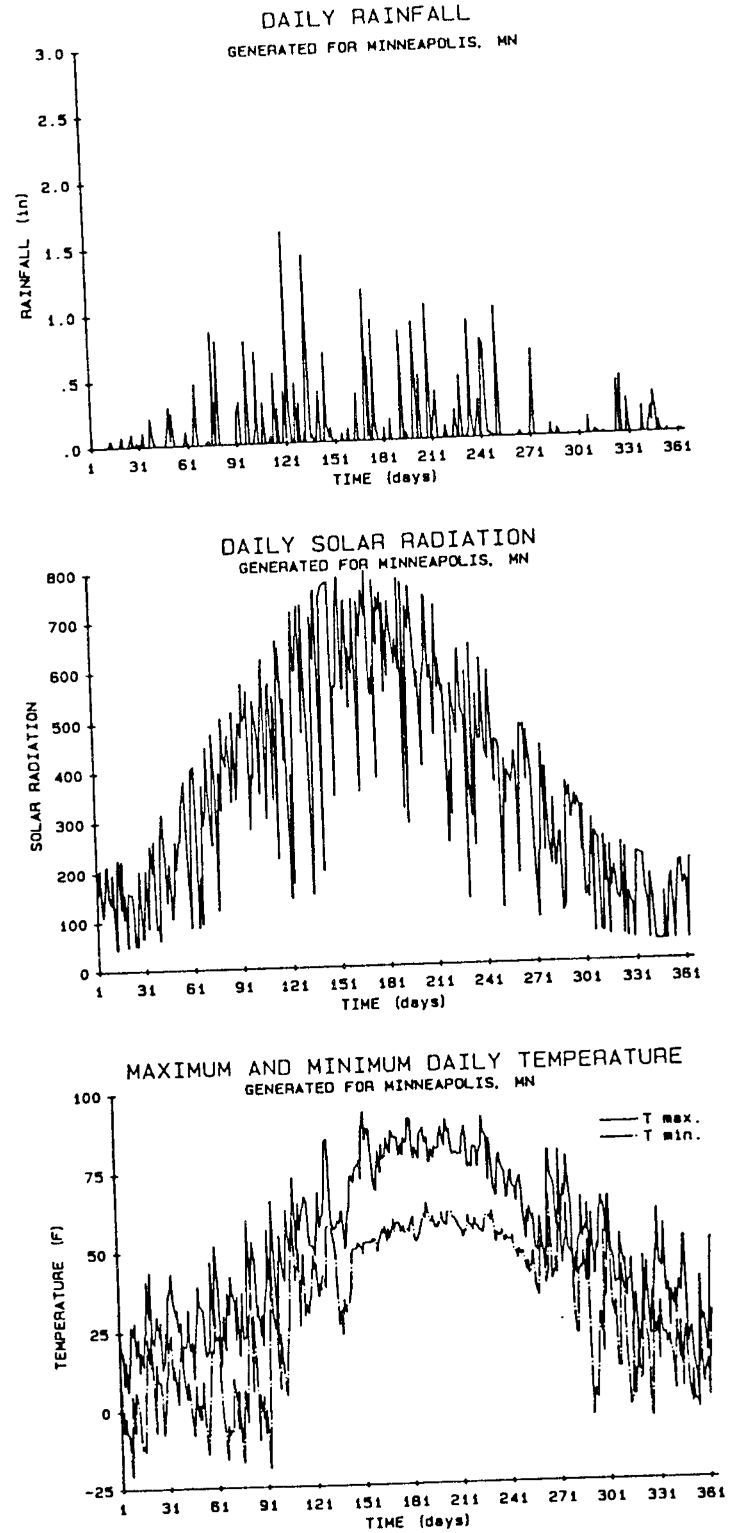
Estimation of effective precipitation

In the design and operation of irrigation systems it is becoming increasingly important to account for the contribution that natural precipitation makes to meeting the consumptive water use of crops. This is more important today than in previous times because of the increase in competition for available high quality water.

Natural precipitation which contributes to the consumptive use requirements of crops is defined in irrigation terminology as being effective precipitation. This definition of the term effective precipitation is in sharp contrast to the conventional definition of the term as used by hydrologists concerned with runoff from rainfall. In hydrology the use of the term refers to the rainfall which produces runoff.

To estimate effective precipitation it is necessary to perform soil water balance calculations so as to facilitate the estimation of runoff, deep percolation and evapotranspiration. This estimation can be accomplished through the application of equation (1). Effective precipitation is then calculated from the expression

$$EP = I - DP \qquad (2)$$


DAILY RAINFALL
GENERATED FOR MINNEAPOLIS, MN
RAINFALL (in)
3.0
2.5
2.0
1.5
1.0
.5
.0
1
31
61
91
121
151
181
211
241
271
301
331
361
TIME (days)
DAILY SOLAR RADIATION
GENERATED FOR MINNEAPOLIS, MN
SOLAR RADIATION
800
700
600
500
400
300
200
100
0
1
31
61
91
121
151
181
211
241
271
301
331
361
TIME (days)
MAXIMUM AND MINIMUM DAILY TEMPERATURE
GENERATED FOR MINNEAPOLIS, MN
T max.
T min.
TEMPERATURE (F)
100
75
50
25
0
-25
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31
61
91
121
151
181
211
241
271
301
331
361
TIME (days)

Figure 1.

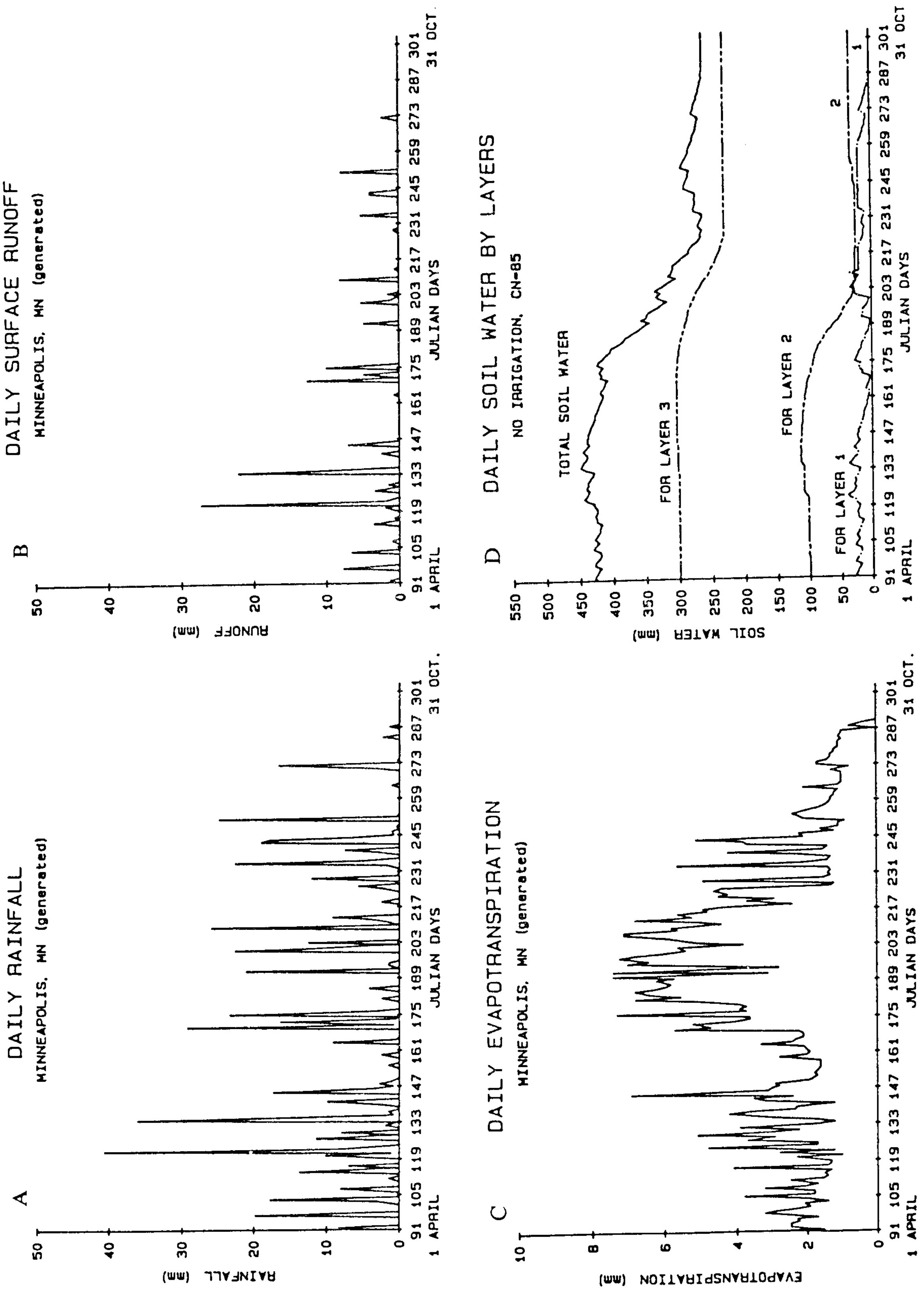
A
DAILY RAINFALL
MINNEAPOLIS, MN (generated)
RAINFALL (mm)
50
40
30
20
10
0
91 105 119 133 147 161 175 189 203 217 231 245 259 273 287 301
1 APRIL
31 OCT.
JULIAN DAYS
B
DAILY SURFACE RUNOFF
MINNEAPOLIS, MN (generated)
RUNOFF (mm)
50
40
30
20
10
0
91 105 119 133 147 161 175 189 203 217 231 245 259 273 287 301
1 APRIL
31 OCT
JULIAN DAYS
C
DAILY EVAPOTRANSPIRATION
MINNEAPOLIS, MN (generated)
EVAPOTRANSPIRATION (mm)
10
8
6
4
2
0
91 105 119 133 147 161 175 189 203 217 231 245 259 273 287 301
1 APRIL
31 OCT.
JULIAN DAYS
D
DAILY SOIL WATER BY LAYERS
NO IRRIGATION, CN=85
SOIL WATER (mm)
550
500
450
400
350
300
250
200
150
100
50
0
TOTAL SOIL WATER
FOR LAYER 3
FOR LAYER 2
FOR LAYER 1
2
1
91 105 119 133 147 161 175 189 203 217 231 245 259 273 287 301
1 APRIL
31 OCT
JULIAN DAYS

Figure 2.

where EP is the effective precipitation during a given period of time. The time period used for design purposes is generally selected to be one month.

According to the criterion set by the SCS (1967), effective precipitation in any given month cannot exceed the amount of evapotranspiration in that month. This criterion is adopted in this report and can be expressed as

$$EP < ET \qquad (3)$$

To illustrate the estimation of effective precipitation the SWBM described in the previous application was used to solve equation (1) for monthly total values of I, DP, and ET. Then effective precipitation was calculated with equation (2) subject to equation (3).

The location selected for the estimation of effective precipitation is Minneapolis, MN. The weather data generated in the demonstration of WGEN above was used here. The SWBM was applied to the weather data with the input parameters used in the demonstration of SWBM above. No supplemental irrigation water was applied during the simulation period although SWBM has the option for application of irrigation water. The output yielded the monthly effective precipitation for the months of April through October.

For the one year examined it is observed that the natural precipitation contributes a significant part of the monthly consumptive use (ET) by the crop. The values of EP for the months of April and May exceed the monthly ET value and according to equation (3) should be reduced to the ET value.

QUANTIFYING AND MODELING VARIABILITY OF SOIL WATER

This section presents some examples of soil water spatial variability exploration with the semi-variogram. Also presented here is the use of the semi-variogram in kriging to obtain the estimates to map contours of soil water content and their variances.

The semi-variogram

Understanding the nature of the variability of the soil water system can greatly benefit water resources planning. It is possible to predict water deficit or surplus, and determine the effects of changes in the input variables even with generated data.

The semi-variogram is one of those tools, which can help to understand the variability of the soil water system for any area of interest. It gives a visual, quite easy to understand picture, and gives a tangible perspective to the analysis.

The semi-variogram could be seen as a plot of correlation of properties at two different points in space with respect to separation distances (h). The covariance and the semi-variogram are inversely proportional to each other; the former decreases while the latter increases with increasing separation distances.

The steeper the semi-variogram line (i.e., vertical increment is much larger than horizontal increment), the greater the correlation. In other words, a horizontal line means no correlation. Visualize the following, if you are in alfalfa field and know the soil water content where you are standing (point A), start walking, and you would expect that the more you walk away from A the more different the water content will be at the new point. Thus, when the separation distance is great, a measured property will tell little about the property at the second point.

For a detailed discussion of semi-variograms see *Mining Geostatistics* by Journel and Huijbregts (1978). With these concepts behind, we can examine the application of semi-variograms to analysis of the spatial variability of soil water.

Soil water variability. Some of the sources for soil water variability are climatic conditions, topographic factors, soil properties, and soil cover. A more detailed discussion of the sources of soil water variability can be found in (Nieber and Lopez Bakovic, 1987). Climatic conditions are difficult to accurately predict, so efforts went to other factors that affect soil water variability are more quantifiable and change more slowly. One of these is location in a plane (x,y).

It is possible to explain soil water variability as a function of its location in a plane by using at transmissivity values for groundwater aquifers. Semi-variograms have been used with success in groundwater studies. But, when a similar analysis was carried for soil water (down to a 130 cm soil depth) of a forest catchment in Texas, the water content was not significantly correlated to separation distances in the plane. See Figure 3a.

The effect of separation distances in a three-dimensional location of the soil surface at the place of measurement yielded similar results: no significant correlation (Figure 3b). Hence, another analysis just with differences in soil surface elevation as separation distance (h) was performed. Here, a significant correlation was observed; see Figure 3c. Since planar distances were much greater than elevation differences, the three-dimensional analysis filtered out the effect of elevation in explaining soil water variability. This suggests using normalized locations. Other factors were also analyzed, such as curvature. For more detail refer to Lopez Bakovic (1987), or contact the author.

In similar fashion, the semi-variogram may be used for exploring correlation of soil water properties to the different sources of variability. It can be used to evaluate and rank these sources according to their importance for the area of interest. For example, an agricultural field plot with just slight elevation differences may show more correlation with separation distances in a plane. Furthermore, differences in percent of clay may also be used as a "separation distances", and they might explain variability quite well indeed. This case was not considered here, because the available information about soil texture in our Texas demonstration area, the Broaddus 5 catchment, suggested that differences were small.

The traditional use of the semi-variogram -- separation distances in a plane -- may be expanded to run a multivariate analysis. Most of the important sources of variability for any property can then be considered, and their use for a given area scale will describe the primary sources for variability at the scale being considered.

Semi-variogram relation to kriging. The semi-variogram is a very important component of kriging; even more, kriging "depends" on the former. It determines the weighting factors for the interpolation. It should be emphasized that kriging may perform very poorly as an interpolator when the semi-variogram being used is in great error. Because semi-variograms are not difficult to develop, they should be carefully examined to insure that a meaningful one is used.

Developing semi-variogram models. We developed experimental semi-variograms based on measurements of soil water at 23 different tube locations that were monitored with a neutron probe. Several options of separation distances (h)were used: one-, two- or three-dimensional locations distances, differences curvature or slope, etc. The experimental semi-variogram was then used to find a "theoretical" semi-variogram that can be described as a simple function; eg., one linear (Figure 4a) and one exponential (Figure 4b).

The points obtained for the experimental semi-variogram are calculated using the equation:

$$\gamma_k^* = \frac{1}{2N^k} \sum^{N^k} [\, z(\mathbf{x}_i) - z(\mathbf{x}_j) \,]^2 \quad \text{For} (h_{k-1} < h < h_k) \qquad (4)$$

where Z(x) is the measured soil water content located at elevation x, and Nk is the number of points found with:

$$\frac{1}{2} [\, Z(\mathbf{x}_i) - Z(\mathbf{x}_j)]^2 \qquad (5)$$

for the increment of separation distance h considered.

The semi-variogram was seen to be highly dependent on soil water contents. That is, for lower soil water contents in the catchment the resulting semi-variogram shifted upward, indicating a greater variance, and vice versa. It was also seen that for soil water content measured down to a depth of 55 cm, the correlation in the x,y-plane increased, appearing as significant (Figure 3d).

The analysis was carried out for a forested catchment (Broaddus 5, TX.) of 10.71 acres. The 23 neutron probe monitored locations range from a minimum separation of 50 feet to a maximum separation of 800 feet. For shorter distances, usually with smaller elevation differences, the nugget effect (i.e., constant, no correlation) is obtained in the semi-variogram. This means that with the measured soil water values, nothing can be said of variability for smaller separation distances. In reality soil water content is a continuous property (i.e., no jumps in values take place under normal conditions), and the intercept should be zero.

Kriging

Kriging is a simple linear interpolator developed by D. G. Krige (1951). It estimates the value of properties at a location with the equation:

$$\text{Est} = \text{Sum}(b_i * Z_i) \qquad (6)$$

It is powerful and unbiased and produces minimum variance for the estimated value. The weighting factors are given values that fulfill these conditions for each point being estimated.

A contour plot of soil water contents was developed from the semi-variogram obtained in the previous analysis (Figure 5b). The weighting factors are obtained solving the linear system of equations:

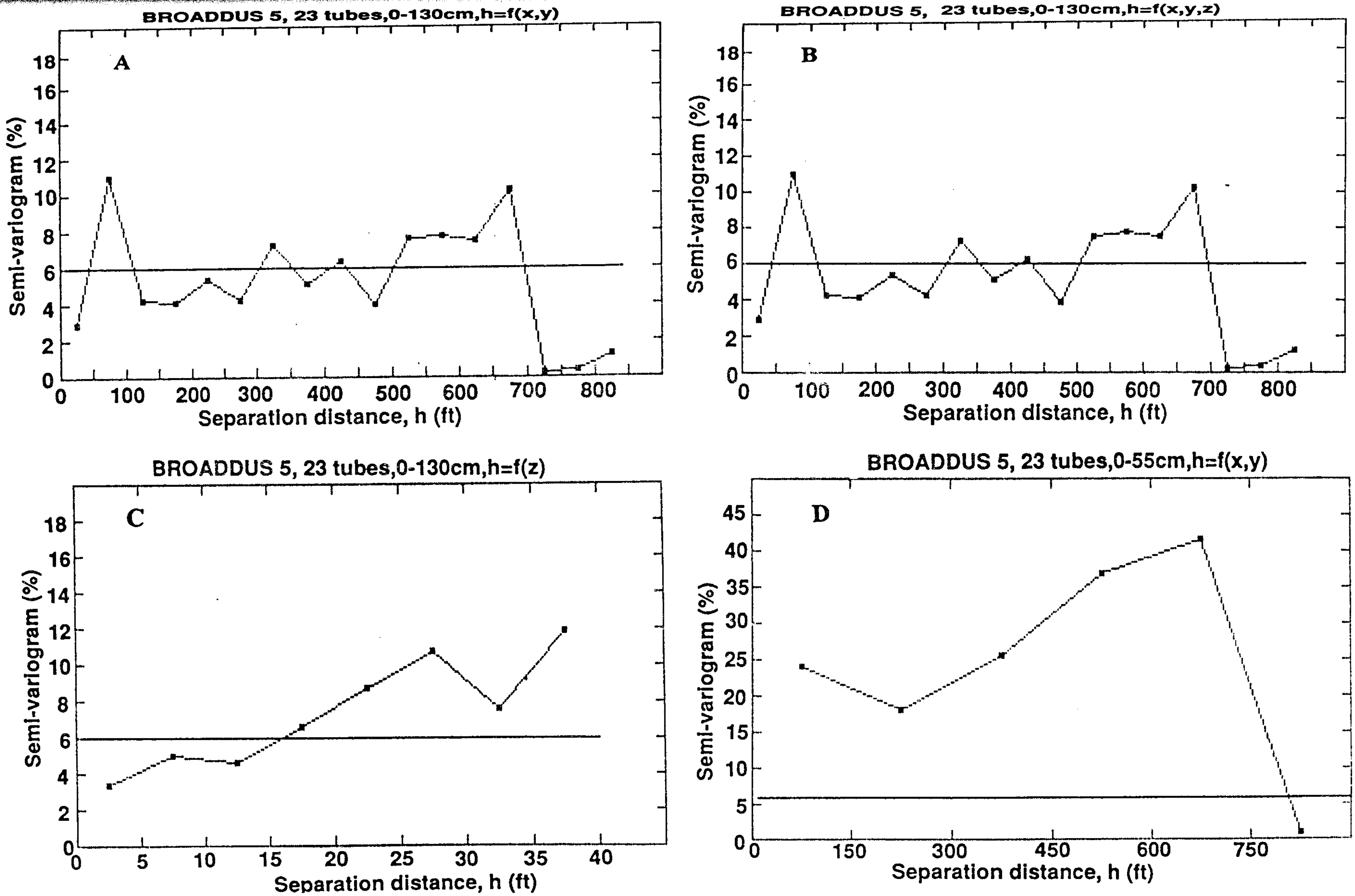

Figure 3. Semi-variograms for soil water (down to a 130 cm soil depth) of a forested catchment in Texas showed that the water content was not significantly correlated with separation distances form the place of measurement in the plane or in a three-dimensional soil surface (A and B). Analysis using elevation as

$$[A]\{x\} = \{b\} \qquad (7)$$

where [A] is a matrix (N+1) by (N+1), {x} is a vector of N number of weights and a lagrangian multiplier, {b} is a vector (N+1), and N is the number of measurements being used for the interpolation. Both, [A] and {b} are filled using the semi-variogram. The lagrangian multiplier insures that the sum of all weights equals one.

The weighting factors are calculated for each new point being estimated. The soil water measured at points farther from the point of estimation are given a lower weight so that they have less influence in the value being estimated. While soil water values were estimated, their corresponding variances (ie.,the error squared) were also evaluated. A contour map of variances is presented in Figure 5c. The soil water contours closely resemble the elevation contours. This is expected because the soil water contents were highly correlated to elevation differences in this catchment.

Figure 5d shows the soil water contours that were obtained by using the correlation to separation distances on the plane (x,y). Here the contours do not resemble the elevation contours. The lack of strong correlation between soil water contents and separation distances in the x,y-plane was seen with the semi-variogram analysis. Hence, it would be expected from the soil water estimates with the semi-variogram, that using differences in elevation would be more reliable than simple location.

SUMMARY AND CONCLUSIONS

This report demonstrated two methods of soil water simulation with example applications of soil water balance models and spatial variability models.

We performed the calculation of a soil water balance at a point with the SWBM equation with artificially generated weather variables of precipitation, maximum and minimum air temperature, and solar radiation. The results agreed with the general notion that drier antecedent moisture conditions produce less runoff.

We used semi-variogram and kriging techniques to model the spatial variability of soil water. Semi-variograms have been used with success in groundwater studies. But, our similar analysis of soil water (down to a 130 cm soil depth) in a forested catchment in Texas showed that the water content was not significantly correlated to separation distances in the plane. Nor was separation distance in a three-dimensional location of the soil surface able to produce satisfactory results at the place of measurement. Another analysis with differences in surface elevation was performed, producing a significant correlation Because planar distances were much greater than elevation differences, the three-dimensional analysis the greater magnitude of the planar distance numbers gave them greater weight, resulting in a reduced effect of elevation in explaining soil water variability. This suggests that techniques to give variables equal weight should be examined.

We found the semi-variogram to be highly dependent on soil water contents. That is, for lower soil water contents in the catchment the resulting semi-variogram shifted upward, indicating a greater variance, and vice versa.

In the analysis carried out for a forested catchment in Texas shorter distances, usually with smaller elevation differences, produced no correlation in

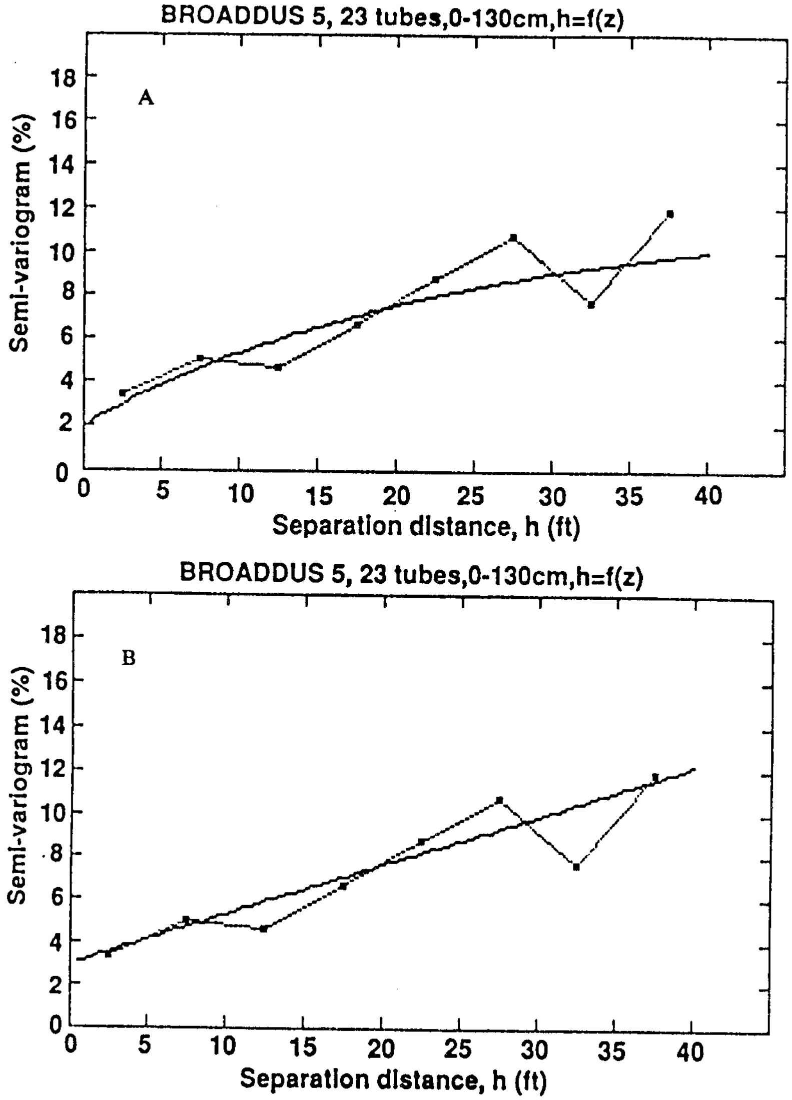

Figure 4. Plots of the "experimental semi-variogram" are presented here together with the proposed "theoretical semi-variograms":

$$Z'(x) = \sum_{i=1}^{N} \lambda_i Z_i(x_i)$$

where:
Z' = estimate
Z_i = ith measurement
λ = weights
x = location vector (x,y,...)
N = number of measurements

a) Linear, $\gamma(h) = C_0 + \theta * h$ $(C_0 = 3, \theta = 0.23)$

b) Exponential, $\gamma(h) = C_0 + s^2\left(1 - e^{-\frac{h}{a}}\right)$ $(C_0 = 2, s^2 = 10, a = 25)$

(A "nugget" (C_0) was added to both semi-variogram models)

These are the semi-variograms for soil water content as a function of elevation differences (h). As the difference h between two points increases, the correlation between their soil water content decreases; i.e., the covariance decreases, and the semi-variogram increases in value.

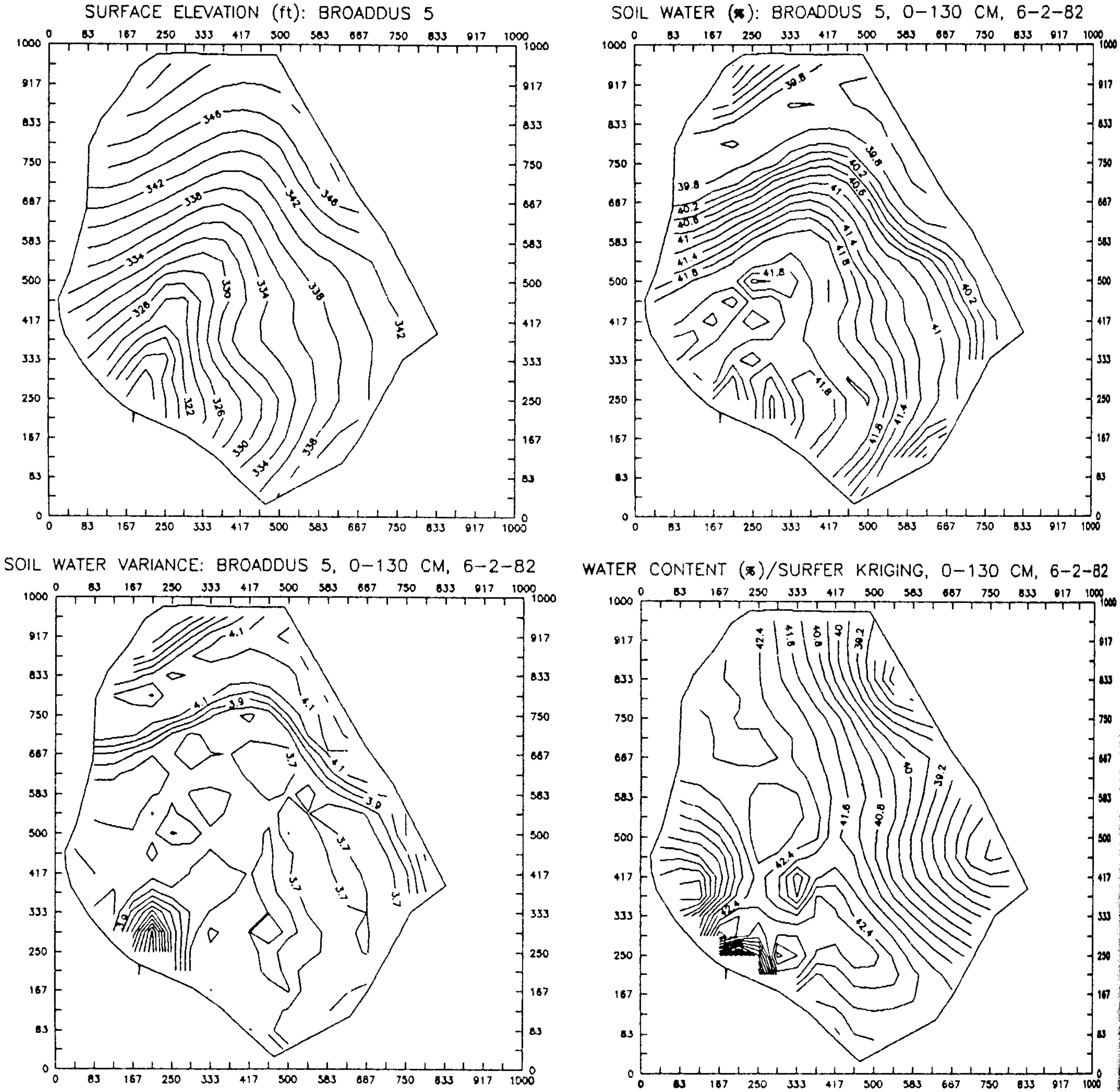

Figure 5. Kriging is a very powerful interpolator. It give both the interpolated estimate and its variance (i.e., estimation error). Map A shows the elevation contour map for a forested area, Broaddus 5, in Texas. Map B is a contour plot of soil water content generated using "kriging" with a linear semi-variogram that is a function of elevation differences (shown in a Figure 4). Map C displays the variances (i.e., standard deviations squared) for the estimated soil water contents in contours. The soil water contour map D was generated for the same conditions as B, but using kriging with Surfer, by Golden Software Incorporated.

the semi-variogram. This means that with the measured soil water values, nothing can be said about variability for smaller separation distances.

When we weighted values with kriging techniques the soil water contours closely resembled the elevation contours. This is expected because the soil water contents were highly correlated to elevation differences for this catchment in our semi-variogram analysis.

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