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Allah Bakhsh  
*Iowa State University*

Ramesh S. Kanwar  
*Iowa State University, rskanwar@iastate.edu*

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# Spatio-Temporal Analysis of Subsurface Drainage Flow Volumes

## **Abstract**

Understanding the effects of spatio-temporal variability on subsurface drainage volumes will help in minimizing the adverse environmental effects on the health of ecological systems. The objectives were to investigate the spatial structure and temporal stability of subsurface drainage trends using six years (1993 to 1998) of field measured data from 36 experimental plots. Two main components of variability (i.e., the large-scale deterministic structure or trend and the small-scale stochastic component) were studied using the median polishing technique and variography. Normalized trend surfaces indicated that trend patterns were stable over the study period. After subtracting the trend from subsurface drainage data, the residuals were used during the subsequent variography. The semivariogram analysis showed a strong spatial structure for most of the years, although the spatial parameters of sill and nugget were found to be different for each year because of climatic effects. The spatial correlation lengths, however, were found to be consistent from year to year at 190 m. Total variance in subsurface drainage data was partitioned between the large-scale deterministic component and the small-scale stochastic component. On average, variations in the trend accounted for about 36% of the total variance, and sill values represented about 64% of the variance. The greater contribution of the stochastic component and stable patterns in the trend surfaces revealed that subsurface drainage flow volumes were controlled by the intrinsic soil and landscape properties. These results indicated that stable trend surfaces can be used as a guide to delineate the agricultural management zones where best management practices can be applied to reduce the negative environmental effects resulting from the discharge of subsurface drainage effluents to surface water bodies such as creeks and streams.

## **Keywords**

Detrending, Median polishing technique, Semivariogram analysis

## **Disciplines**

Agriculture | Bioresource and Agricultural Engineering | Water Resource Management

## **Comments**

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# SPATIO-TEMPORAL ANALYSIS OF SUBSURFACE DRAINAGE FLOW VOLUMES

A. Bakhsh, R. S. Kanwar

**ABSTRACT.** Understanding the effects of spatio-temporal variability on subsurface drainage volumes will help in minimizing the adverse environmental effects on the health of ecological systems. The objectives were to investigate the spatial structure and temporal stability of subsurface drainage trends using six years (1993 to 1998) of field measured data from 36 experimental plots. Two main components of variability (i.e., the large-scale deterministic structure or trend and the small-scale stochastic component) were studied using the median polishing technique and variography. Normalized trend surfaces indicated that trend patterns were stable over the study period. After subtracting the trend from subsurface drainage data, the residuals were used during the subsequent variography. The semivariogram analysis showed a strong spatial structure for most of the years, although the spatial parameters of sill and nugget were found to be different for each year because of climatic effects. The spatial correlation lengths, however, were found to be consistent from year to year at 190 m. Total variance in subsurface drainage data was partitioned between the large-scale deterministic component and the small-scale stochastic component. On average, variations in the trend accounted for about 36% of the total variance, and sill values represented about 64% of the variance. The greater contribution of the stochastic component and stable patterns in the trend surfaces revealed that subsurface drainage flow volumes were controlled by the intrinsic soil and landscape properties. These results indicated that stable trend surfaces can be used as a guide to delineate the agricultural management zones where best management practices can be applied to reduce the negative environmental effects resulting from the discharge of subsurface drainage effluents to surface water bodies such as creeks and streams.

**Keywords.** Detrending, Median polishing technique, Semivariogram analysis.

The development of an hypoxia zone in the Gulf of Mexico has been attributed to the nitrate-nitrogen ( $\text{NO}_3\text{-N}$ ) loadings in the Mississippi and Atchafalaya rivers, whose combined discharge account for 80% of the total inflow into the Gulf of Mexico (Rabalais et al., 2001). The  $\text{NO}_3\text{-N}$  contamination of surface water and groundwater bodies in the midwestern parts of the U.S. have been associated with  $\text{NO}_3\text{-N}$  loadings in subsurface drainage water from agricultural lands (Kanwar et al., 1997; Jaynes et al., 1999). The  $\text{NO}_3\text{-N}$  concentrations in the Mississippi river have been reported to be higher in the tributaries emanating from Illinois, Iowa, and Minnesota, where over 30% of the agricultural lands use subsurface drainage (Randall, 1998; Hatfield et al., 1998). In addition, several studies have concluded the significant role of subsurface drainage in transporting  $\text{NO}_3\text{-N}$  from the bottom of the root zone to the edge of the field (Kanwar and Bakhsh, 2001; Kanwar et al., 1999; Jaynes et al., 1999; Randall and Mulla, 2001; Bakhsh et al., 2000a).

David et al. (1997) determined, in their six-year study period, that an average of 49% of the pool of residual  $\text{NO}_3\text{-N}$

remaining in the soil after harvest was leached through drains and exported to the river. Goolsby et al. (2001) reported that higher precipitation could influence  $\text{NO}_3\text{-N}$  in two ways. First, stream flow can be larger and more  $\text{NO}_3\text{-N}$  will be transported unless concentrations decrease. Second, the higher volume of flow would leach more accumulated  $\text{NO}_3\text{-N}$  from soils and would actually cause  $\text{NO}_3\text{-N}$  concentrations to increase. Similar scientific evidence has indicated that nitrogen levels build up in soils during dry years from mineralization processes and reduced uptake by crops, providing more nitrogen to be flushed out in the succeeding wet years (Randall, 1998). These results suggest the critical role of subsurface drainage in transporting  $\text{NO}_3\text{-N}$  from agricultural lands. Randall and Mulla (2001) concluded that the least economical ways to reduce  $\text{NO}_3\text{-N}$  loadings to surface water would be to abandon the subsurface drainage systems or find alternate ways to minimize their adverse effects.

The volume of subsurface drainage flow from a given field is the integrated effect of climate, landscape, soil properties, and management factors. Bakhsh et al. (2002) reported significant linear relationships between growing season precipitation and subsurface drainage flow volume, and between subsurface drainage flow volume and  $\text{NO}_3\text{-N}$  leaching losses with subsurface drainage water. They also reported that variability in subsurface drainage flow volume existed on a field-to-field basis even when the fields were under the same management practices. Therefore, it becomes important to study the spatial and temporal structure of the subsurface drainage flow trends on a long-term basis as a means to develop sustainable management practices to

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The authors are **Allah Bakhsh ASAE Member Engineer**, Post-Doctoral Research Associate, and **Ramesh S. Kanwar, ASAE Member Engineer**, Professor and Chair; Department of Agricultural and Biosystems Engineering, Iowa State University, Ames, Iowa. **Corresponding author:** Ramesh Kanwar, 102 Davidson Hall, Iowa State University, Ames, IA 50011; phone: 515-294-1434; fax: 515-294-6633; e-mail: rskanwar@iastate.edu.

mitigate the environmental effects resulting from subsurface drainage (Bakhsh et al., 2000b).

The spatial structure of a random variable, such as subsurface drainage flow volume, from a given field can consist of a large-scale deterministic structure or trend and a small-scale stochastic component (Cressie, 1991). Trend can be studied using the median polishing technique for data collected on a regular grid (Jaynes and Colvin, 1997). After removal of the trend from subsurface drainage flow data, residual values can be used to study the small-scale stochastic component of variability using variogram analysis (Bakhsh et al., 2000b). A variogram presents the spatial variability between data points as a function of the distance separating them and determines the extent of spatial relationships. Therefore, this study was designed to investigate the trends in subsurface drainage flow data on a

long-term basis and to determine the extent of spatial dependence in the subsurface drainage flow data with the following specific objectives:

- To compare the spatial and temporal trends in subsurface drainage flow data measured from 36 experimental plots over a period of six years (1993 to 1998) using the median polishing technique.
- To investigate the extent of spatial correlations in the subsurface drainage flow volumes using variogram analysis.

## MATERIALS AND METHODS

The study area consisted of 36 field experimental plots (each  $76 \times 58.5$  m) located at the Iowa State University's northeastern research center near Nashua, Iowa. The soils at the site (fig. 1) include Floyd loam (fine-loamy, mixed,

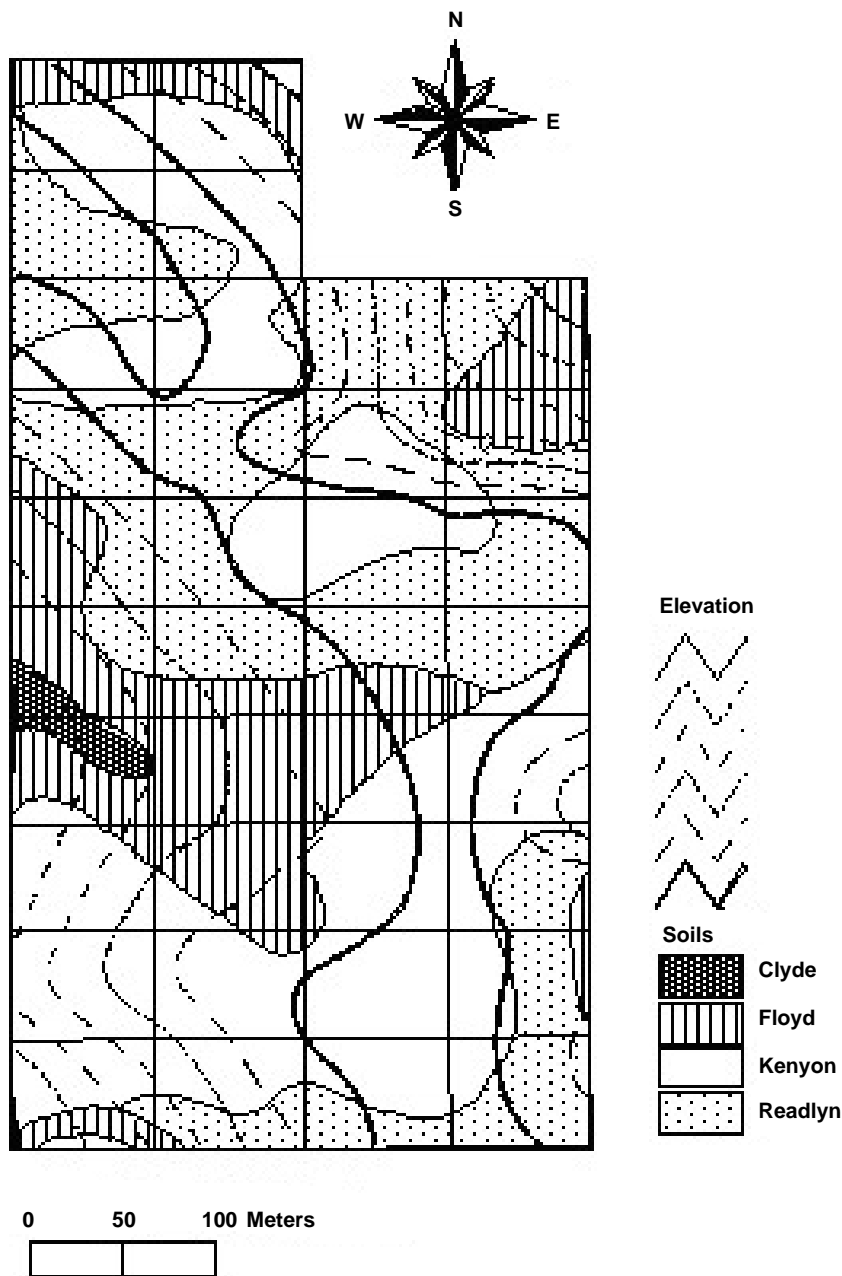


Figure 1. Soil type, topography, and plot layout of the study area at Nashua, Iowa.

**Table 1. Descriptive statistics for subsurface drainage data collected from 36 plots over a six-year period (1993 to 1998) at Nashua, Iowa.**

Statistic	1993	1994	1995	1996	1997	1998	Average (1993–1998)
Subsurface Drainage Data (mm)							
Mean	387	82	137	62	100	228	166
Median	370	67	108	53	72	213	103
Standard deviation	153	62	103	42	85	115	150
Skewness	0.89	2.3	2	1.8	2	1.6	1.6
Kurtosis	1.7	4.9	4	3.4	4.4	3.7	2.7
Minimum	66	22	14	16	2.1	44	2.1
Maximum	781	287	464	185	377	588	781
Interquartile range	140	36	63	31	67	82	177
Coefficient of variation (%)	39	75	75	67	85	51	90
Median Polished (trend) Drainage Data (mm)							
Mean	369	76	119	58	89	217	154
Median	363	64	109	51	76	208	100
Standard deviation	105	39	61	27	54	89	128
Skewness	-0.04	1.7	1.2	1.6	1.6	0.8	1.3
Kurtosis	-0.13	2.2	1.6	2.3	2.3	1.1	0.9
Minimum	139	32	19	19	23	56	19
Maximum	607	182	277	129	249	457	607
Interquartile range	155	37	54	22	41	77	157
Coefficient of variation (%)	28	52	51	47	61	41	83
Residual Transformed Drainage Data, log <sub>e</sub> (mm)							
Mean	0.03	0.0	0.09	-0.04	0.0	0.04	0.02
Median	0	0	0	0	0	0	0
Standard deviation	0.4	0.5	0.5	0.8	0.9	0.4	0.6
Skewness	-0.4	-0.9	0.8	-3.4	-1.9	1.1	-2.2
Kurtosis	2.2	2.9	1.5	17.7	8.7	2.5	15.2
Minimum	-1.1	-1.6	-1.0	-3.9	-3.7	-0.5	-3.9
Maximum	0.8	0.8	1.7	1.2	1.5	1.4	1.7
Interquartile range	0.3	0.4	0.4	0.4	0.5	0.4	0.4
Growing Season (March to November) Rainfall (mm)							
Rainfall	1030	750	800	680	750	980	840 <sup>[a]</sup>

[a] 30-year average.

mesic Aquic Hapludoll), Kenyon loam (fine-loamy, mixed, mesic Typic Hapludoll), and Readlyn loam (fine-loamy, mixed, mesic Aquic Hapludoll) (Kanwar et al., 1997). From 1978 to 1992, the study area was under four tillage treatments (chisel, moldboard, ridge, and no-till systems) with continuous corn and corn-soybean rotation systems. In 1993, tillage treatments were reduced to two (chisel and no-till systems) while increasing the nitrogen management treatments at the site under the same crop sequence. More details on the experimental treatments at the study area can be found in Bakhsh et al. (2002).

The site has a seasonally high water table and, therefore, benefits from the subsurface drainage installed in 1979. Subsurface drains were installed in the center of each plot (east-west) at 28.5 m spacing at approximately 1.2 m depth. Cross-contamination of the field plots was prevented by installing drain lines along the north and south borders of each plot. East and west borders of each plot were isolated by growing a 9 m grass strip (Bjorneberg et al., 1998). The central subsurface drainage lines were connected to individual sumps for measuring drainage effluent and collecting water samples for chemical analysis. The sumps have an automatic flow-recording mechanism using data loggers. Cumulative subsurface drain flows were recorded two times per week beginning from mid-March to the beginning of December during the entire study period. A more detailed

description of the automated subsurface drainage flow recording system can be found in Kanwar et al. (1999).

#### STATISTICAL ANALYSIS

Descriptive statistics of the subsurface drainage data were calculated using the PROC UNIVARIATE procedure (SAS, 2000). The normality distribution of the data and the presence of extreme values were checked using box plot criteria and normal probability graphs (Ott, 1988; pp. 56, 587). The layout of the 36 field experimental plots (fig. 1) formed a regular grid (76 × 58 m) with the center of each plot as a data point. The large-scale spatial structure or trend was separated using the median polishing technique (Cressie, 1991, p. 46). The median polishing technique has been derived from a simple additive model (Hoaglin et al., 1985; p. 69), with centering of the row and column medians to zero through an iterative process until further adjustments to row medians and column medians are negligible. A detailed procedure for developing the median polishing algorithm can be found in Hoaglin et al. (1985; pp. 69–70). The technique divides the grid values of subsurface drainage effluent into a summation of the overall median ( $\bar{m}$ ), a row effect ( $\bar{r}$ ), a column effect ( $\bar{c}$ ), and a residual term ( $R_{ij}$ ). Trend values ( $T_{ij}$ ) are determined as:

$$T_{ij} = \bar{m} + \bar{r} + \bar{c} \quad (1)$$

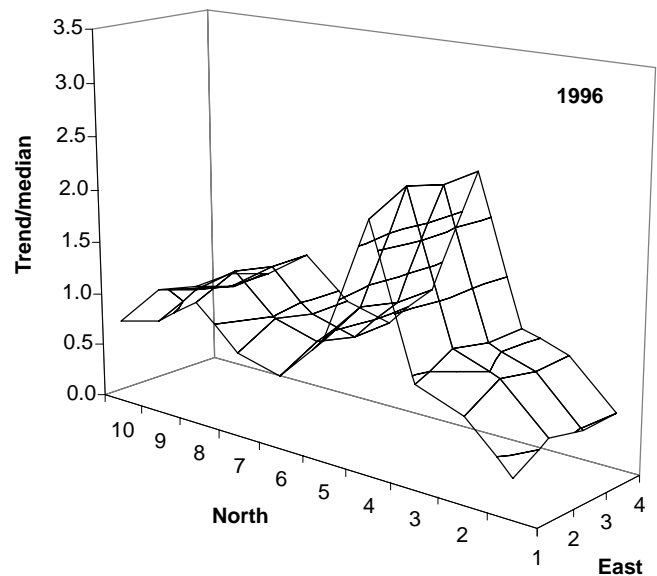
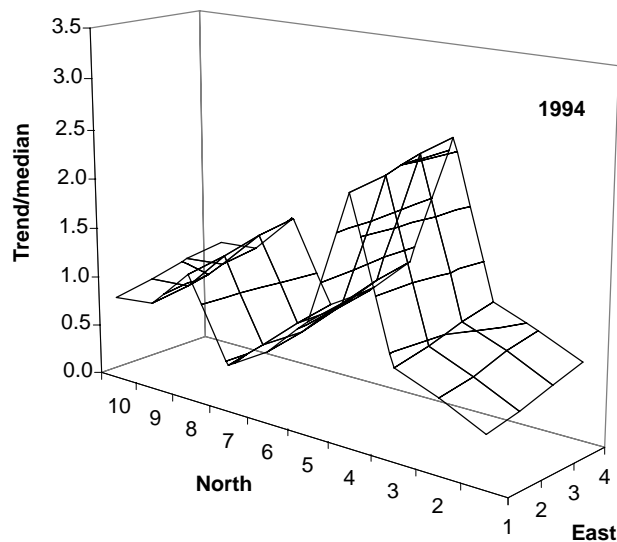
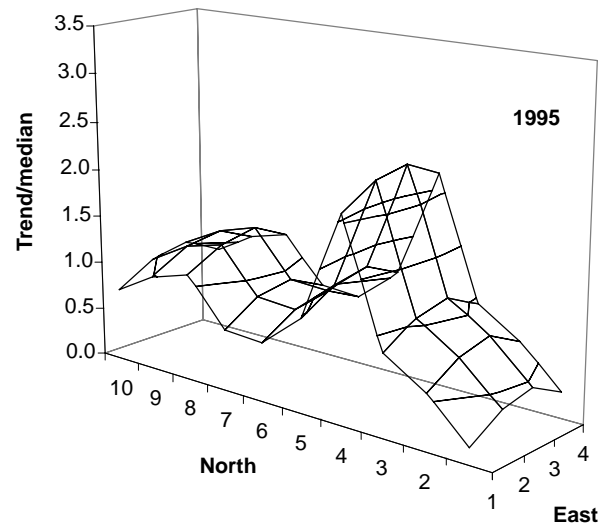
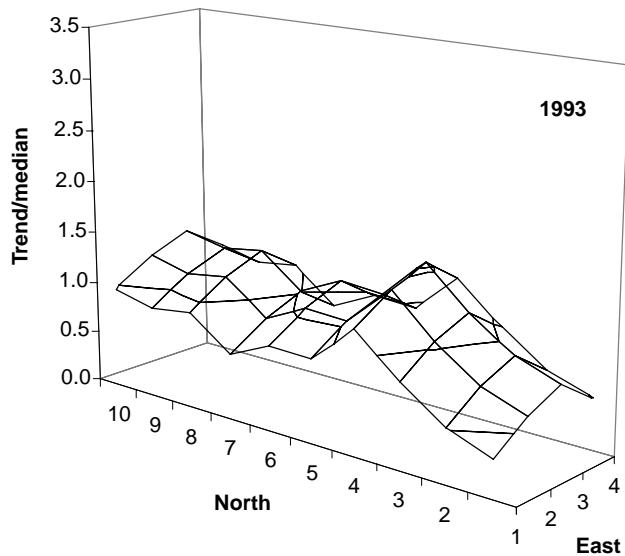


Figure 2. Normalized trend surfaces estimated by median polishing technique for 1993 and 1994.

Figure 3. Normalized trend surfaces estimated by median polishing technique for 1995 and 1996.

where subscripts  $i$  and  $j$  are the row and column numbers of the grid, respectively. In order to compare trend data over the years, which were affected by the changing rainfall conditions from year to year, trend values ( $T_{ij}$ ) were normalized by dividing each value by the median of that year. Before performing variography, raw subsurface drainage data were transformed ( $\log_e$ ) to reduce non-stationarity of the mean and variance and non-normality of the data (Mohanty and Kanwar, 1994). Transformations of data helped simplify the underlying model, linearize the data, and stabilize the variances (Ott, 1988, p. 313).

The transformed data were detrended using the transformed trend data ( $D_{ij}$ ) estimated by the median polishing technique:

$$D_{ij} = \bar{m} + \bar{r} + \bar{c} + R_{ij} \quad (2)$$

The median polishing technique may not capture all of the large-scale trends, as the trend orientation is not known a priori (Cressie, 1991, p. 48). Therefore, an additional term was included in equation 2 to detect any further diagonal trend in the polished data:

$$D_{ij} = \bar{m} + \bar{r} + \bar{c} + g(i - \bar{i})(j - \bar{j}) + R'_{ij} \quad (3)$$

where  $\bar{i}$  and  $\bar{j}$  are the average row and column numbers, respectively. To detect this additional trend, a regression analysis between the  $R_{ij}$  and  $(i - \bar{i})(j - \bar{j})$  terms was done with zero intercept to check the significance level of the slope ( $g$ ). The  $R'_{ij}$  values are the second step residuals after regression analysis. The residual data were again checked for normality and extreme outlier values using the box plot criteria (Bakhsh et al., 2000b):

$$\text{Lower boundary for extreme outliers: } Q1 - 3(IQR)$$

$$\text{Upper boundary for extreme outliers: } Q3 + 3(IQR) \quad (4)$$

where  $Q1$ ,  $Q3$ , and  $IQR$  are the lower quartile, upper quartile, and interquartile ranges, respectively. One value of extreme outlier was identified each year and was replaced by the trend estimate determined from the median polishing technique.

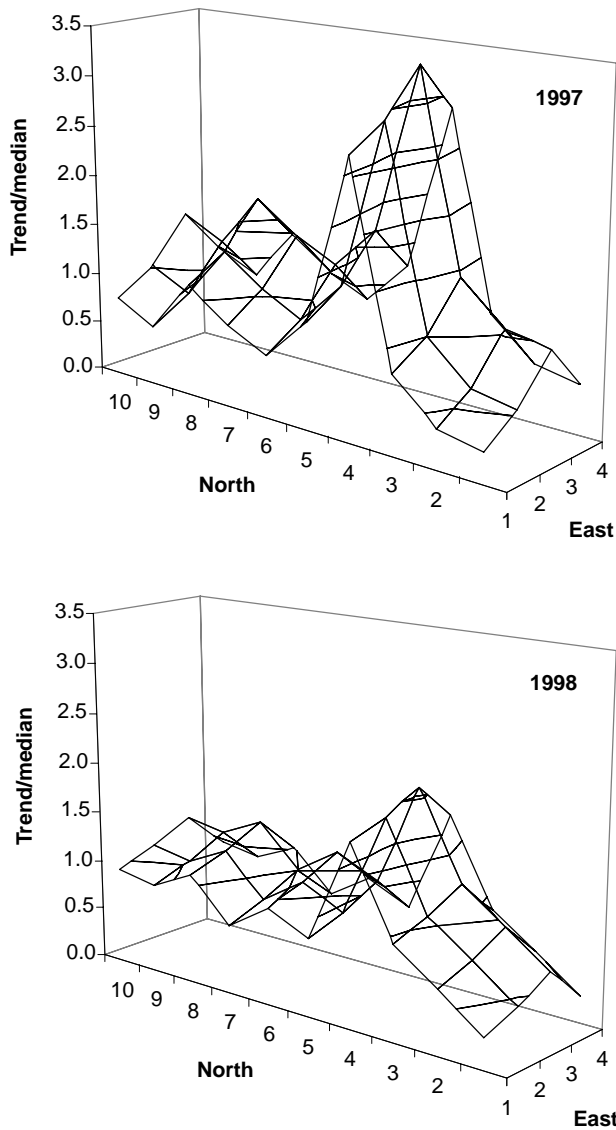


Figure 4. Normalized trend surfaces estimated by median polishing technique for 1997 and 1998.

Histograms and normal probability graphs were made to check the normal distribution of the data before performing variography because of the underlying assumption of Gaussian distribution (Jaynes and Colvin, 1997). The mild outliers were not replaced because the approximate straight lines of the normal probability plots did not violate the assumption of normality (Ott, 1988; p. 587).

#### STOCHASTIC VARIABILITY

After subtracting the transformed trend from the transformed drainage data (eq. 2), residual values were used in variography analysis because any obvious trend has to be removed before computing the semivariogram (SAS, 2000). Lag distance and lag numbers were selected at the distance where at least 30 data pairs were included in computing a single value of the experimental variogram. The maximum lag distance was restricted from 1/2 to 3/4 of the diameter of the region containing the data (SAS, 2000). Experimental variograms were calculated using the PROC VARIOGRAM procedure (SAS, 2000). Isotropic conditions were verified using the DIRECTION statement at 0, 60, 90, and 120 de-

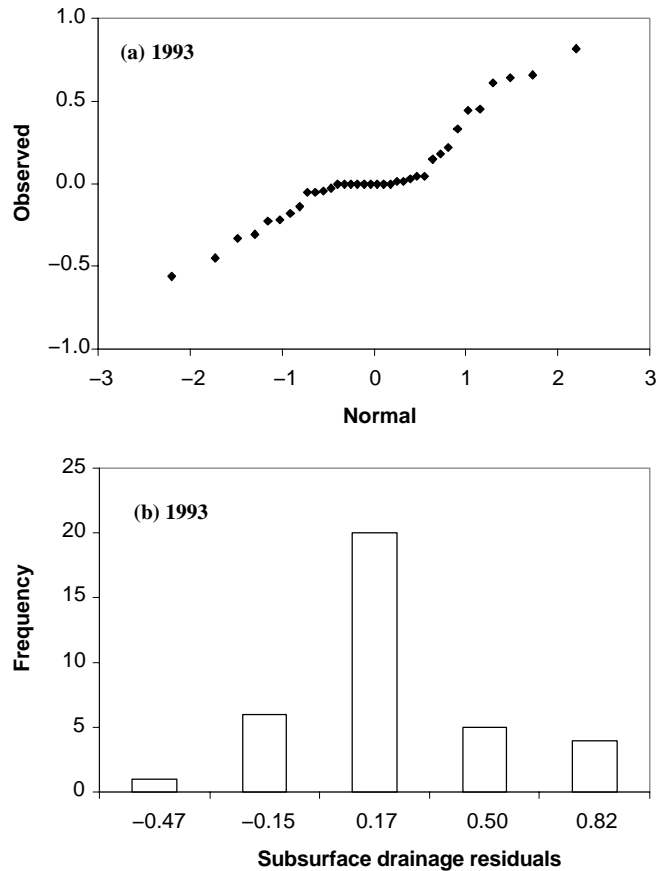


Figure 5. Normal probability plot (a) and histogram (b) of subsurface drainage residuals for 1993.

grees from true north. SAS estimated the semivariance, which is defined as:

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [Z(x_i) - Z(x_i + h)]^2 \quad (5)$$

where  $\gamma(h)$  is the semivariogram estimator for lag distance  $h$ ,  $Z$  is the drainage residual value at locations  $x_i$  and  $x_{(i+h)}$ , and  $N(h)$  is the total number of data pairs.

There are various methods of fitting a variogram model such as the least squares, maximum likelihood, and robust methods (Cressie, 1991; p. 90). These techniques are not appropriate for data sets resulting in a small number of variogram points (SAS, 2000). Instead, a visual fit (Hosseini et al., 1993) of variogram points to a few standard models is often satisfactory. Different models were tested for fitting the data. A spherical model was found as the best fit based on the significance level of  $r^2$  between predicted and experimental values (Novak et al., 1997). The spherical model is defined as:

$$\gamma(h) = c_o + c_s \left[ \frac{3h}{2a} - \frac{h^3}{2a^3} \right] \quad 0 < h \leq a \quad (6)$$

$$\gamma(h) = c_o + c_s = c \quad h > a \quad (7)$$

where  $h$  is the lag distance (m) between pairs,  $c_o$  is the nugget,  $c_s$  is the spherical component,  $c$  is the sill, and  $a$  is the range of the semivariogram. Another model, called the exponential

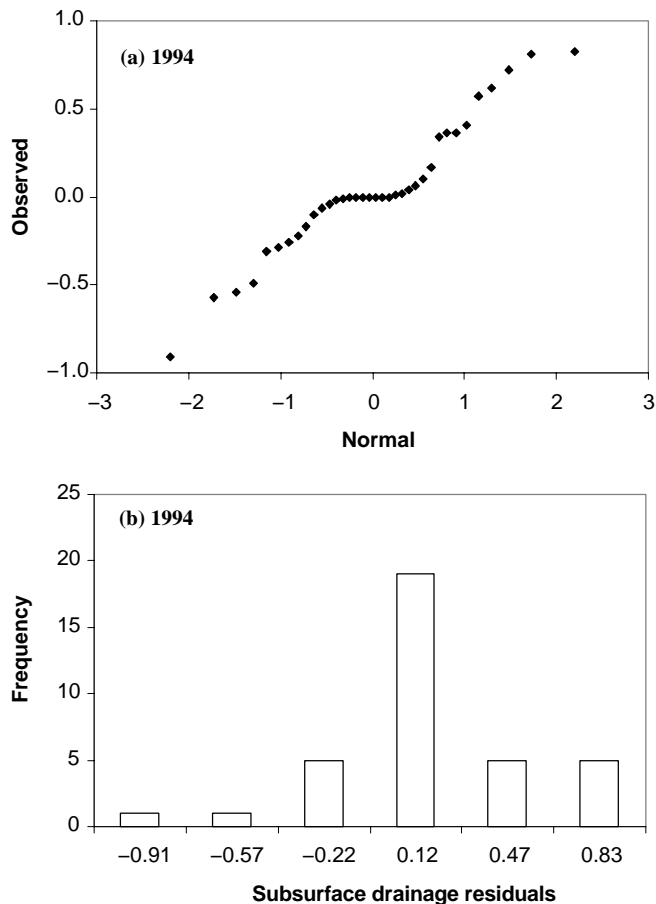


Figure 6. Normal probability plot (a) and histogram (b) of subsurface drainage residuals for 1994.

model, was also found as the best fit to the experimental variogram data for some of the years and is defined as:

$$\gamma(h) = c_o + c_e[1 - \exp(-h/a)] \quad 0 < h \leq d \quad (8)$$

where  $c_e$  is the exponential component, and  $d$  is the maximum lag distance of variogram computations.

The total variance in the subsurface drainage data ( $\log_e$  transformed) was partitioned between the large-scale deterministic structure and the small-scale stochastic component using the PROC CORR COV procedure (SAS, 2000).

## RESULTS AND DISCUSSION

The average annual (March to November) subsurface drainage volume varied from a low of 62 mm in 1996 to a high of 387 mm in 1993, showing the effect of rainfall variability on subsurface drainage flow rates (table 1). The growing season (March through November) rainfall varied from 680 mm in 1996 to 1030 mm in 1993. The rainfall affected the subsurface drainage flow volumes because a significant ( $P = 0.05$ ) correlation ( $R^2 = 0.89$ ) was reported between the subsurface drainage flow volume and the growing season rainfall for the study area (Bakhsh et al., 2002). The year 1993 was wet, having 23% greater rainfall compared to the 30-year average annual rainfall of 840 mm (Voy, 1995). All other years with rainfall amounts of 750 mm for 1994, 800 mm for 1995, and 750 mm for 1997 were lower

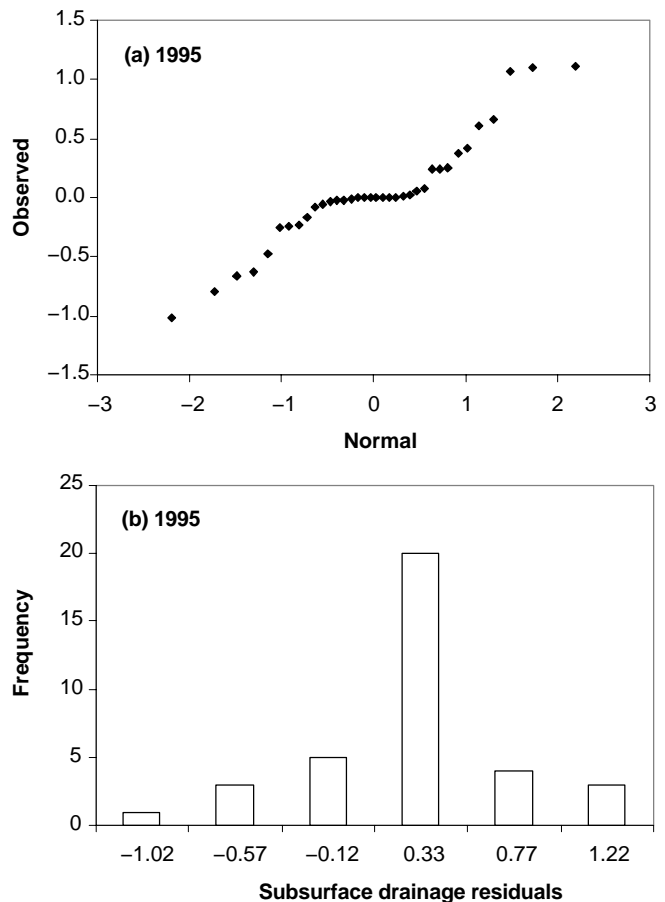


Figure 7. Normal probability plot (a) and histogram (b) of subsurface drainage residuals for 1995.

than the 30-year average annual rainfall, except rainfall of 980 mm for 1998, which was 17% more than the 30-year average annual rainfall. The 6-year average subsurface drainage (166 mm) showed that about 20% of the average growing season rainfall (832 mm) resulted in subsurface drainage flow for this area.

The coefficient of variation (CV) ranged from 39% in 1993 to 85% in 1997, illustrating the effect of spatial variability on subsurface drainage flow volumes from the 36 field plots (table 1). In addition, CV seems to be dependent on the rainfall conditions because the minimum CV was observed in 1993, which was a very wet year when all the field plots had a substantial amount of subsurface drainage volume. The above-average rainfall reduced the variability in subsurface drainage flow rates during those years (1993 and 1998). The below-average rainfall years showed higher CV values, and the spatial effect was more pronounced in those years (1994 to 1997). Minimum subsurface drainage volume ranged from 2 mm in 1997 to 66 mm in 1993. Similarly, maximum subsurface drainage volume varied from a low of 185 mm in 1996 to a high of 781 mm in 1993 (table 1). These results support the role of spatial variability in soil properties affecting the subsurface drainage flow rates, resulting in variable spatial and temporal trends in subsurface drainage data.

### TREND SURFACES

The large-scale deterministic structure of subsurface drainage data was determined using the median polishing



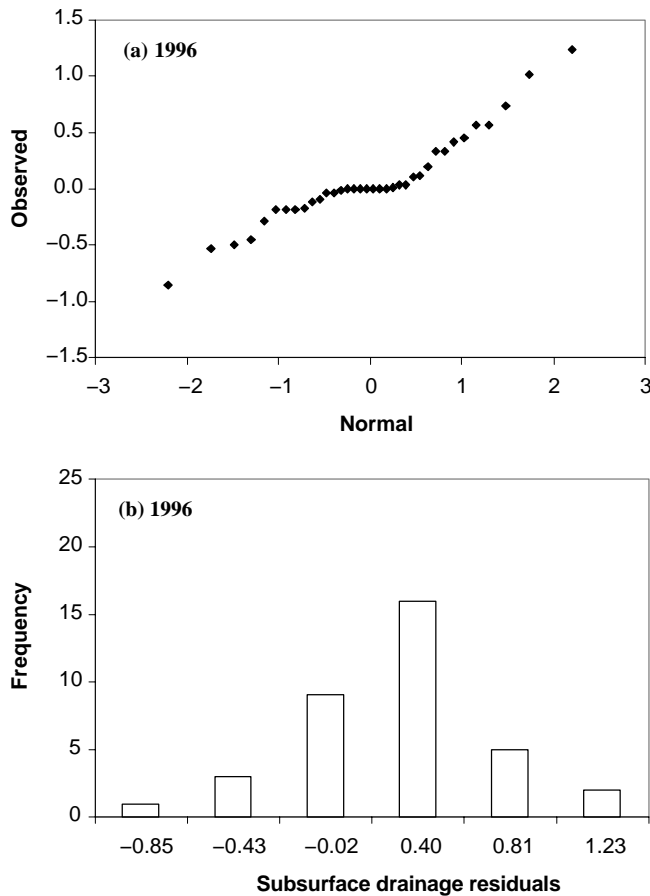


Figure 8. Normal probability plot (a) and histogram (b) of subsurface drainage residuals for 1996.

technique. The normalized trend surfaces showed very clear and persistent trends over the six-year study period (figs. 2 to 4). The diagonal component of the trend was not detected because slope  $g$  (eq. 3) was not significantly ( $P < 0.05$ ) different from zero. This shows that the median polishing technique was able to capture most of the trend existing in the data along row and column directions.

The variability in rainfall from year to year also affected the trend surfaces. The normalization of trend surfaces reduced the climatic effects on the trend surfaces for the ease of comparison over the years. However, trend surfaces of the years having rainfall greater than the normal (1993 and 1998) showed relatively smooth surfaces in comparison to the years having rainfall below normal (1994 to 1997). Comparison of trend surfaces showed higher trend surfaces for the 4th and 5th columns toward the north (figs. 2 to 4). Similarly, low trend surfaces were observed in the south of the site at the 1st and 2nd columns, and after crossing the high trend surfaces toward the north at the 7th and 8th columns. It was interesting to note the stability of trend patterns, especially the high trend surfaces, despite the fact that there was significant variability in rainfall amounts over these years. The stable linear features showing higher trend surfaces were more likely due to intrinsic soil and landscape properties of topography, soil type, etc. (fig. 1).

Histograms and normal probability plots of subsurface drainage flow volume residuals show that much of the skewness present in the original data has been removed through transformation ( $\log_e$ ) and subtraction of the trend

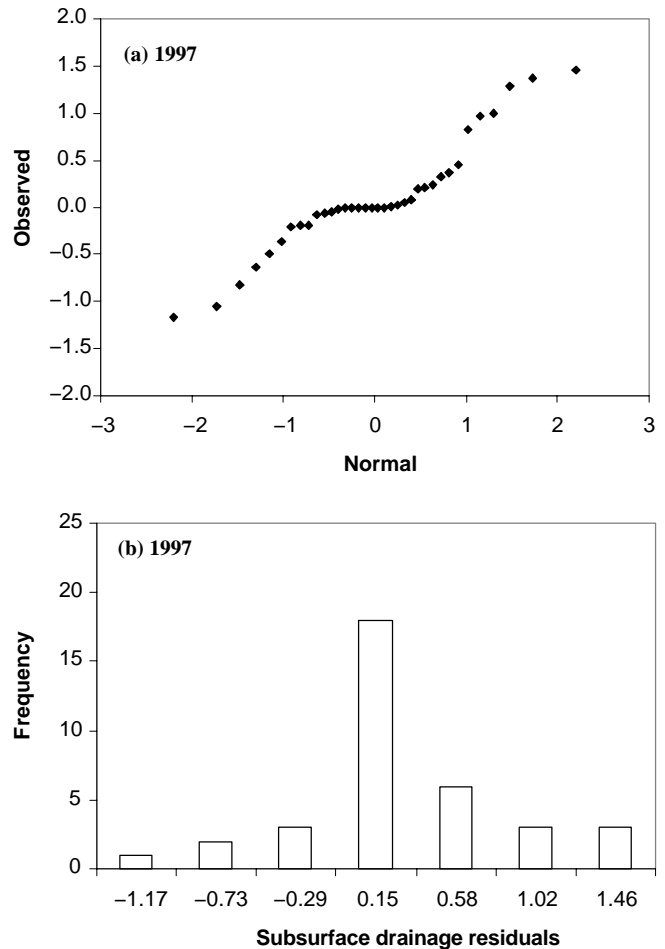


Figure 9. Normal probability plot (a) and histogram (b) of subsurface drainage residuals for 1997.

determined from the median polishing technique (figs. 5 to 10), although some degree of negative skewness still exists because of mild outliers, which were not removed. Only extreme outliers (one value each year) were detected by box plot criteria and were replaced by the trend estimates. However, the approximate straight lines of the normal probability plots (figs. 5 to 10) show that the assumption of normal distribution was not violated (Ott, 1988; p. 587).

#### SPATIAL ANALYSIS

Semivariogram analysis showed a strong spatial structure in drainage flow rates for most of the years, although the spatial parameters of nugget and sill were different for each year. The 1993 variogram showed zero nugget effect because 1993 was a very wet year and the CV for this year was less in comparison to all other years (table 1). A spherical model was fitted to the experimental variogram data showing highly significant ( $P < 0.01$ ) correlation ( $R^2 = 0.96$ ) between experimental and modeled data. The semi-variance reached a constant value (sill = 0.12) at the spatial correlation distance of 190 m (fig. 11a). The year 1994 was a dry year and showed a nugget effect of 0.07 and a range of 190 m with a sill value of 0.18. A low nugget value and a high sill-to-nugget ratio indicate that there was less small-scale variability in the subsurface drainage data (fig. 11b) for this year. The year 1995 showed a similar spatial structure to that of 1994 with a nugget value of 0.05. The sill value of 0.27 was high

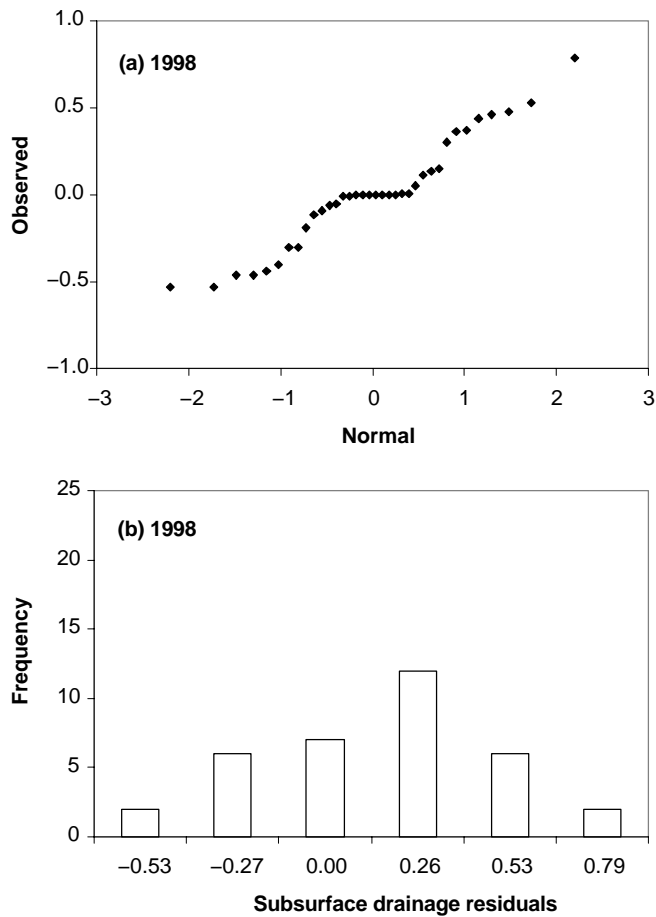


Figure 10. Normal probability plot (a) and histogram (b) of subsurface drainage residuals for 1998.

compared with that of 1994 and the sill-to-nugget ratio was higher, showing less variability at small-scale level along with a range value of 190 m (fig. 12).

The year 1996 had the lowest rainfall during the 6-year period and, therefore, showed a different spatial structure when compared with variograms of 1993 to 1995. An exponential model was found to be the best fit showing a highly significant relationship ( $P < 0.01$ ) with  $R^2 = 0.95$ . The year 1996 showed a nugget effect of 0.08 and a sill value of 0.17. The sill-to-nugget ratio was low, indicating the existence of small-scale variability. The nugget value contributed about 47% of the total variance and showed spatial dependence at about 190 m distance. Similarly, the year 1997 showed a strong spatial structure similar to the variograms of 1993 to 1995 with sill = 0.44, nugget = 0.04, and range = 190 m (fig. 13). The spherical model showed a highly significant ( $P < 0.01$ ) relationship ( $R^2 = 0.96$ ) with the experimental variogram data. The nugget effect accounted for about 10% of the total variance with a high sill-to-nugget ratio. The 1998 data showed a different spatial structure in comparison to the previous years (1993 to 1997), probably because of its above-average rainfall. The nugget effect accounted for 66% of the total variance and showed a lower sill-to-nugget ratio (1.5), indicating that small-scale variability was more pronounced in this year. An exponential model was found to be the best fit model to the experimental variogram data for 1998 with  $R^2 = 0.84$  (fig. 13).

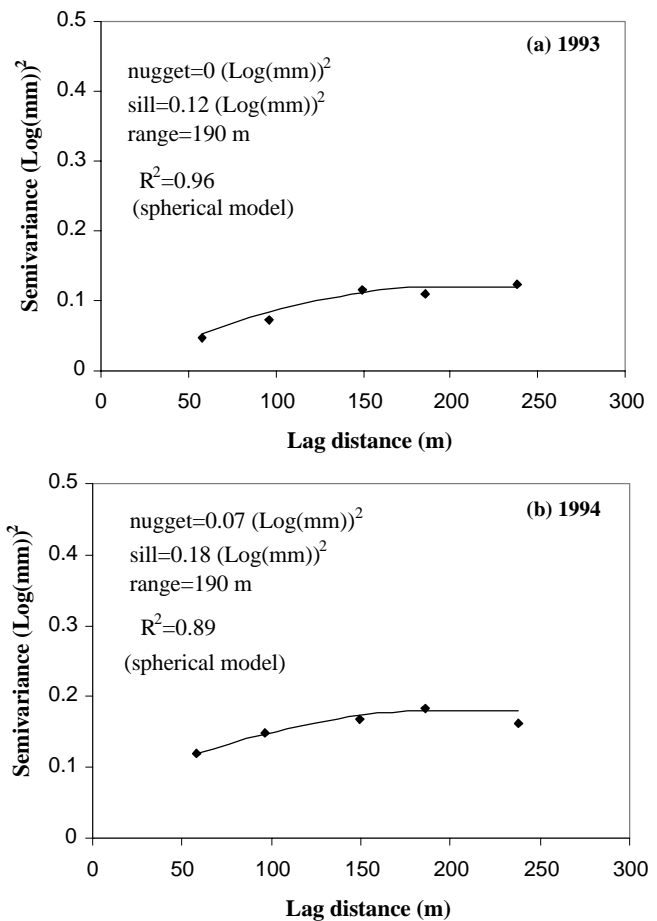


Figure 11. Experimental and model-fitted variograms of subsurface drainage residuals for 1993 (a) and 1994 (b).

The spatial structure in subsurface drainage flow data seems to be influenced by the variability in rainfall from year to year. Although there was variation in the nugget and sill values, the range was found to be consistent from year to year (i.e., 190 m). Subsurface drainage flow from a field plot is the integrated effect of soil properties, climate, and landscape attributes. The integrated effects of the soil and landscape attributes were mainly governed by the rainfall variability, which ranged from 19% below the 30-year average rainfall in 1996 to 23% greater than the 30-year average rainfall in 1993. This rainfall variability also affected the coefficient of variation, which ranged from 39% in 1993 to 85% in 1997 (table 1). The nugget effect, however, can also be attributed to the drain spacing effect and small size of the sample (Jaynes and Colvin, 1997). This analysis shows how rainfall variability affected the total variance and sill-to-nugget ratio when there was not much change in the spatial correlation distance over the study period. Although variation was observed in sill and nugget values over the years, probably due to changing climatic conditions, no significant relationship was found between precipitation and sill or range values for the study area.

The variance in subsurface drainage data was partitioned between the large-scale deterministic structure or trend and the small-scale stochastic component. On average, trend accounted for about 36% of the total variance and sill values represented about 64% of the variance. The minimum trend contribution towards total field variance was found to be 17%

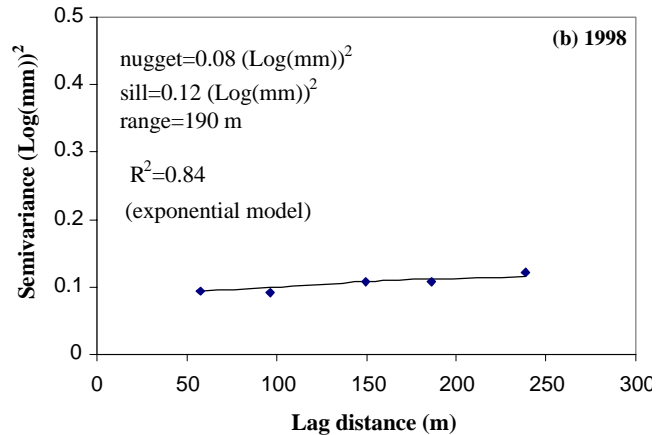
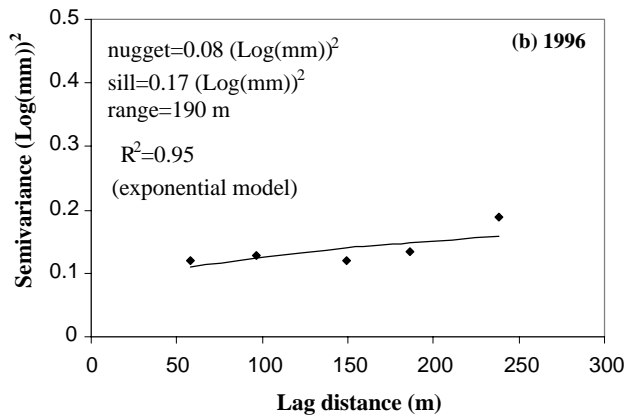
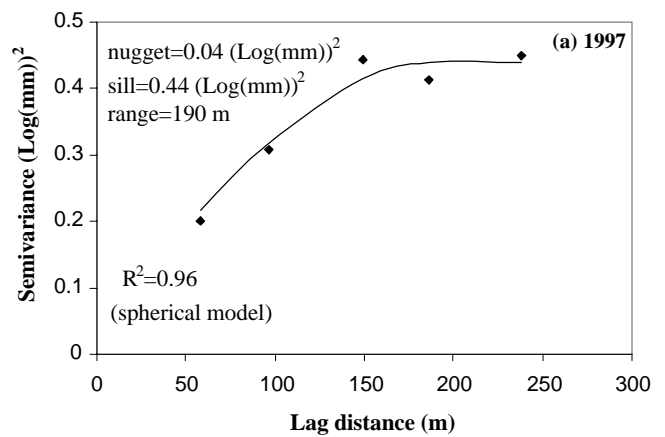
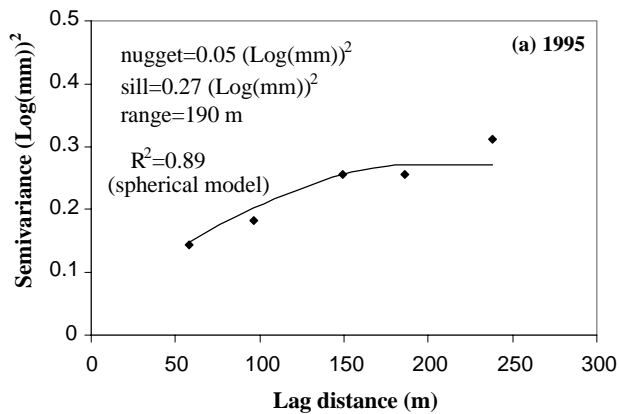


Figure 12. Experimental and model-fitted variograms of subsurface drainage residuals for 1995 (a) and 1996 (b).

Figure 13. Experimental and model-fitted variograms of subsurface drainage residuals for 1997 (a) and 1998 (b).

in 1996 and the maximum of 54% occurred in 1998. Similarly, the stochastic component contribution ranged from a low of 46% in 1998 to a high of 83% in 1996. This corresponds very well to the rainfall amount of 19% below the 30-year average in 1996 and 17% above the 30-year average in 1998. The higher contribution of the stochastic component and the stable patterns of the trend surfaces revealed that subsurface drainage effluents were controlled by the intrinsic soil and landscape properties (topography, soil type, till index parameters, etc.) despite significant effects ( $P < 0.05$ ) of rainfall variability on the subsurface drainage volumes over the years.

## SUMMARY AND CONCLUSIONS

Six years of data (1993 to 1998) on subsurface drainage volumes were used to study the spatial and temporal trends using the median polishing technique. The large-scale deterministic structure or trend values were divided by the median value for the respective year to compare the normalized trend surfaces over the study period for ascertaining stability in the trends. The median polishing technique was found to be successful in identifying the trend surfaces because the additional diagonal component of the trend was not detected and the regression analysis showed that slope was not significantly ( $P < 0.05$ ) different from zero. Comparison of the trend surfaces revealed that trends were found to be stable for most of the years, which showed that variability in subsurface drainage flows were mainly controlled by intrinsic factors, such as the soil and landscape

attributes. Rainfall variability from year to year affected the trend surfaces and the degree of smoothness when compared across years having rainfall below and above average.

Before performing variography analysis, subsurface drainage data were transformed ( $\log_e$ ) and detrended using the median polishing technique. The resulting residuals of subsurface drainage data were checked for an additional diagonal component. One extreme outlier was detected by the box plot criteria each year and was replaced by trend surface estimates because outliers may have biased the semivariogram computation due to the underlying assumption of Gaussian distribution of the data. The subsurface drainage residual data were checked using the histograms and normal probability plots and were used during the subsequent variography.

The semivariogram analysis showed a strong spatial structure for most of the years. The spatial correlation lengths were found to be 190 m. The sill values ranged from 0.12 for 1993 and 1998 (years with above-average rainfall) to 0.44 for 1997 (with below-average rainfall). This fact was also supported by the coefficient of variation, which ranged from 39% in 1993 to 85% in 1997. Higher rainfall reduced the variability, whereas low rainfall increased the variability and affected the sill values of the variograms. The range value of about 190 m did not change from year to year and was most likely controlled by the intrinsic factors of the soil and landscape properties.

The partition of the total variance showed that the large-scale deterministic structure accounted for about 36%

and the small-scale random component contributed about 64% of the variability. The higher contribution of the stochastic component of the variance and the stable patterns of the normalized trend surfaces indicate that the intrinsic factors of soil and landscape properties controlled the variability in subsurface drainage data for this study area. These results indicate that stable trend surfaces can be used as a guide to delineate the agricultural management zones to reduce the negative environmental effects resulting from the subsurface drainage flows.

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