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DETECTING CHANGES IN THE SPATIAL DISTRIBUTION OF NITRATE CONTAMINATION IN GROUND WATER[1]

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ABSTRACT: Many studies of ground water pollution in general and nitrate contamination in particular have often relied on a one-time investigation, tracking of individual wells, or aggregate summaries. Studies of changes in spatial distribution of contaminants over time are lacking. This paper presents a method to compare spatial distributions for possible changes over time. The large-scale spatial distribution at a given time can be considered as a surface over the area (a trend surface). The changes in spatial distribution from period to period can be revealed by the differences in the shape and/or height of surfaces. If such a surface is described by a polynomial function, changes in surfaces can be detected by testing statistically for differences in their corresponding polynomial functions. This method was applied to nitrate concentration in a population of wells in an agricultural drainage basin in Iowa, sampled in three different years. For the period of 1981-1992, the large-scale spatial distribution of nitrate concentration did not show significant change in the shape of spatial surfaces; while the magnitude of nitrate concentration in the basin, or height of the computed surfaces showed significant fluctuations. The change in magnitude of nitrate concentration is closely related to climatic variations, especially in precipitation. The lack of change in the shape of spatial surfaces means that either the influence of land use/nitrogen management was overshadowed by climatic influence, or the changes in land use/management occurred in a random fashion.
(KEY TERMS: spatial distribution; trend surface analysis; nitrate; ground water; water quality; non-point source pollution; agriculture.)

INTRODUCTION

Agriculture has become the leading non-point source of water pollution and estimates suggest it is the single largest source of pollutants, including sediments, nutrients, and pesticides, to water resources (National Research Council, 1989, 1993). Among other water pollution problems related to agriculture, nitrate pollution has been of growing concern. Nitrate contamination from agricultural activities has been reported in almost every state in the United States (Madison and Brunett, 1985). High nitrate loads have continued, or increased in many streams in the country, despite the reduction in point-source contributions as a result of implementation of the Clean Water Act passed in 1972 (Smith *et al.*, 1987, 1993). A survey conducted in Iowa in 1988-1989 showed that for private domestic water supply (DWS) wells that are less than 15 meters deep, 35 percent of sampled wells exceeded 10 mg/L NO_3-N, the maximum contamination level (MCL) set by the U.S. Environmental Protection Agency (USEPA). In some counties in Iowa, approximately 70 percent of DWS wells exceeded the MCL (Hallberg *et al.*, 1990; Kross *et al.*, 1990).

Nitrate pollution has come under increasing study during the past two decades (Commoner, 1972, 1977; Hill, 1978; Aldrich, 1980; Follett, 1989; Hallberg and Keeney, 1993). Studies on the spatial distribution of nitrate in ground water have often relied on one-time investigations. Trends of nitrate contamination in water from individual wells have been reported and in other cases simple summary statistics from well populations have been used to assess temporal changes (Hallberg, 1989). However, studies on changes in spatial distribution of nitrate over a long period of time are lacking. This paper presents a method to assess spatial changes in water quality over time using data from a population of wells in the Big Spring basin, Iowa.

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Big Spring Basin Project

Extensive studies in the Big Spring ground water basin in northeastern Iowa (Figure 1) have been significant in defining agricultural nonpoint source impacts on water quality. Historic data illustrated that regional increases in nitrate in ground water paralleled increasing fertilizer-nitrogen rates and corn acreage since the 1960s (National Research Council, 1993; Hallberg and Keeney, 1993). The hydrology, water quality, agricultural and land-use practices in the Big Spring basin have been studied in detail since 1981 (e.g., Hallberg *et al.*, 1983; Libra *et al.*, 1992; Rowden *et al.*, 1995). The land in the 267 km^2 basin is essentially all used for agriculture. There are no significant urban or industrial areas, no landfills, or other major point sources that may affect ground water quality (Hallberg *et al.*, 1983).

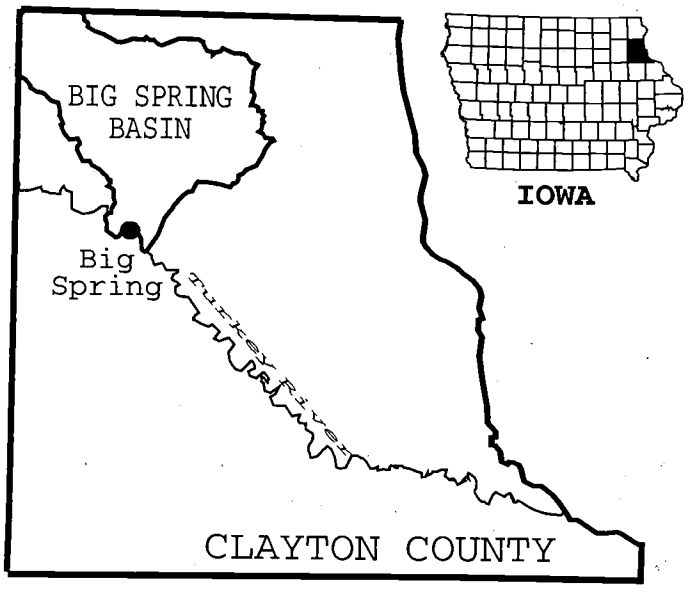

Figure 1. Location of the Big Spring Basin.

The basin is named after Big Spring, the largest ground water spring in Iowa, which discharges from the underlying Galena aquifer, a group of Ordovician-age carbonate rock units. The discharge from Big Spring accounts for nearly 90 percent of the ground water discharged from the basin (Hallberg *et al.*, 1983). The Galena aquifer is unconfined over most of the basin area and is mantled by 1-15 meters of loess and glacial drift. Because of the proximity to the land surface and the existence of some karst features, the aquifer is highly responsive to recharge events and susceptible to a relatively rapid influx of contaminants, including nitrate. The combination of agroecosystems and a responsive hydrogeological system in the basin offers a good setting for studying the impact of non-point source pollution by agriculture (Libra *et al.*, 1992).

The Big Spring ground water basin was defined by detailed field assessments, including water level measurements and site inventories of private water-supply wells in the area, dye-trace studies, identification of gaining and losing stream reaches, installation of dedicated monitoring wells, and compilation of historic records (Hallberg *et al.*, 1983; Littke and Hallberg, 1991).

In addition to the spring and stream monitoring, the Iowa Department of Natural Resources, Geological Survey Bureau conducted basin-wide sampling of private wells in 1981, 1989, and 1992, to assess the water quality in wells used for drinking water. Only those wells finished in the Galena aquifer are used for this study. The number of wells sampled were 99, 197, and 159 for 1981, 1989, and 1992. Among these wells, 71 were sampled in all three years. All are drilled wells finished in the bedrock aquifers. Quality of well construction varies with age, but most are protected and located away from obvious point sources (Hallberg *et al.*, 1983; Hallberg, 1989). The median depth of these 71 wells is 57 meters.

There are many factors that affect the differences and variability in ground water quality among wells (Hallberg, 1989). Well construction and many interrelated hydrogeologic variables are relatively constant when analyzing water-quality data from the same wells over time. All the samplings were carried out during a period of 7-10 days in October of the respective year. This was done to hold to a minimum the effects of short-term weather and hydrologic events and seasonal variability. Among other contaminants, nitrate concentration in water samples was analyzed by the University Hygienic Laboratory (UHL) in Iowa City, a U.S. Environmental Protection Agency certified laboratory. All the nitrate data are presented in this paper as NO_3-N in mg/L.

Spatial Analysis

In spatial analysis, either the observations, or the locations of the sites, or both can be regarded as random quantities (as the case may be). When the observations are those of a random variable (or from a random process), it may be useful to decompose the spatial variation of a random variable into several components, each corresponding to a different scale (Burrough, 1986; Cressie, 1993). The simplest decomposition consists of two parts: large-scale variation

and small-scale variation. This can be expressed as follows:

$$Z(\mathbf{S}) = \mu(\mathbf{S}) + \delta(\mathbf{S}) \quad (1)$$

where $\mathbf{S}$ is the location in a given dimension, usually one, two, or three; $Z(\mathbf{S})$ is the observed data value; $\mu(\mathbf{S})$ is the large-scale variation; and $\delta(\mathbf{S})$ is the small-scale variation. The large-scale variation, $\mu(\mathbf{S})$, is the deterministic mean structure. Its value may remain constant (stationary) throughout the study area, or may change abruptly at a boundary, or may vary continuously with a trend. The small-scale variation, $\delta(\mathbf{S})$, takes the place of the error term in a conventional statistical model; however, $\delta(\mathbf{S})$ is not necessarily a white noise process (identical independent distributions and normal). The small-scale variation can be further decomposed into two parts: spatially correlated random variation and a white noise process (Burrough, 1986); or three parts: smooth small-scale variation, microscale variation, and a white noise process (Cressie, 1993).

There is no absolute standard for what constitutes a large scale, a small scale, or a microscale. The decomposition of spatial variation into different scales is not unique and is largely operational in nature. This means that depending on how much variation is attributed to the components at different scales, we may reach different conclusions on the same set of data (Cressie, 1993). If one assumes that the deterministic element of trend, $\mu(\mathbf{S})$, is constant or nearly so, the variation in the data will be considered as mainly the contribution from the small-scale, random component, $\delta(\mathbf{S})$, in Equation (1). On the other hand, one may also assume, for the same set of data, that a significant trend (or drift) exists. Then, the variation in the data will be considered as a result of the combination of the large-scale smooth variation and the small-scale local variation.

If one assumes that there exists a substantial large-scale variation in the data, a mean function can be constructed to represent it. The most widely used family of mean functions is the family of polynomial functions (Burrough, 1986; Oliver *et al.*, 1989; Cressie, 1993). The independent variables in a polynomial function are mixed monomials in the coordinates of the locations where the data are collected. For example, for data taken from a two-dimensional region, the pth-order polynomial function is given by

$$Z(x,y) = \beta_{00} + \beta_{10}x + \beta_{01}y + \beta_{20}x^2 + \beta_{11}xy + \beta_{02}y^2 + \ldots + \beta_{rs}x^r y^s + \partial(x,y) \quad (2)$$

Where $Z(x,y)$ is the value of a variable Z at the site with coordinates (x,y); $\beta_{00}, \beta_{10}, \ldots, \beta_{rs}$ are unknown parameters; $r+s = p$, the order of the polynomial; and $\partial(x,y)$ is the error component.

Geometrically, a polynomial function corresponds to a smooth surface. When the error components are assumed to be iid (independent and identically distributed normal variables), fitting a polynomial function to the data constitutes the basis of trend surface analysis, which is widely applied in geoscience studies (Burrough, 1986; Davis, 1986).

Although trend surface analysis is mainly used for investigating large-scale spatial variation of a single response variable, it can also be used for examining difference in spatial distribution among several response variables (Zimmerman *et al.*, 1996). If these response variables are observed values of the same single variable, but measured on several occasions, the temporal change in large-scale spatial variation of the variable of interest can be investigated by comparing its trend surfaces at different points in time.

METHODS

In this study, observations of nitrate concentration in sampled wells across the Big Spring basin are considered as realizations of random variables. The spatial variation of nitrate concentration is regarded as a function of well locations, which are measured in UTM coordinates (Universal Transverse Mercator), and well depth.

A model with the general form of Equation (1) is constructed to describe the spatial variation of nitrate concentration. The preliminary analysis of the data showed that nitrate concentration increases from west to east in the Big Spring basin (Figure 2), indicating a non-constant mean structure in the data. This suggests that a mean structure for large-scale variation as expressed in Equation (2) should be included in the model.

The large-scale spatial variation of nitrate distribution can be described as a surface over the basin. We assume that the surface can be specified with a polynomial function of the spatial coordinates of well locations and well depths. The analysis of the nitrate surface in this study does not focus on the spatial distribution per se, but rather on its change, if any, from year to year. To test for change in the large-scale variation of spatial distribution over years, polynomial functions of the nitrate surfaces for different years are compared statistically.

For two polynomial functions to be equal, first of all, they must have the same order, i.e., linear, quadratic, or cubic, etc. The maximum power in the polynomial defines the order of the equation. The order of the polynomial function for a given sampling

year will be determined separately. To determine the order of an appropriate polynomial function for the data, a series of polynomial functions, with successively increasing orders (linear, quadratic, cubic, etc.), is fit to the same data set for a given year. Then, pairwise comparisons of the functions will be conducted from low to high order, in the same fashion as in comparing two regression models (Neter *et al.*, 1985; Weisberg, 1985), using an F test for the difference in residual sum of squares in the two models. When two models, say model 1 and model 2, are compared, with model 2 being a subset of model 1 such that all items in model 2 are also contained in model 1, the following statistic is calculated:

$$\frac{(RSS_2 - RSS_1)/(df_2 - df_1)}{RSS_1/df_1} \tag{3}$$

where RSS_1 is residual sum of squares for model 1; RSS_2 is residual sum of squares for model 2; df_1 is residual degrees of freedom for model 1; df_2 is residual degrees of freedom for model 2. The calculated value will be compared with a table value from an $F_{(df2-df1,df1)}$ distribution.

If the test in one comparison between two functions turns out to be statistically significant, the function with higher order is then compared with the next-higher-order function in the next test. This pairwise comparison continues until two functions do not show significant differences in their residual variances. The function with a lower order in the final test will be the one chosen for the data. The same procedure will be applied to the data for each and every sampling year to determine the orders of the corresponding polynomial functions for all three years. If the order of the polynomial functions varies from year to year, this indicates changes in the spatial distribution of nitrate over years.

On the other hand, even if it turns out that the polynomial functions for nitrate concentration in the basin have the same order for all three sampling years, they may still be significantly different in terms of shape and height of the surfaces. Shape and height of a surface in two or higher dimensions are analogous to slope and intercept of a line in one dimension. Testing for difference in shape and height of surfaces can be performed in a way similar to that in which lines in one dimension are tested for differences in slope and intercept (Weisberg, 1985).

For the purpose of comparison of nitrate surfaces, nitrate data from all three sampling years will be combined as observations of a single random variable. The following model will be fit to the data:

$$NO3(x,y,d,t) = f(x,y,d,t) + \varepsilon(x,y,d,t) \tag{4}$$

where NO3 is the nitrate concentration in the sampled wells; x,y are coordinates of well locations; d is well depth; t is sampling year; i.e., 1981, 1989, and 1992; f is a polynomial function and its order is determined from the aforementioned procedure; ε is the error term.

Since there are three sampling years, the model contains three corresponding surfaces. To test if there is any difference among the three surfaces, two dummy or indicator variables are created to represent the three years:

IND81 = 1, if t=1981
IND81 = 0, otherwise;

IND89 = 1, if t=1989
IND89 = 0, otherwise;

IND81 = 0 and IND89 = 0 if t=1992.

These two indicator variables will take the place of t in the model (Equation 4).

As with the one-dimensional case, a full model and several reduced models will be posited and fit to the nitrate data from all three years, distinguished by the two indicator variables.

After introducing the two indicator variables into the model (Equation 4), several hypotheses can be presented as follows:

Model 1. There is no difference among the three surfaces. The following model is obtained:

$$NO3(x,y,d) = f(x,y,d) + \varepsilon(x,y,d) \tag{5}$$

This model does not contain the two indicator variables because year is assumed to make no difference.

Model 2. Only the height of surfaces is different. The resulting model is:

$$NO3(x,y,d) = IND81 + IND89 + f(x,y,d) + \varepsilon(x,y,d) \tag{6}$$

Model 3. Only the shape of surfaces is different. Then,

$$NO3(x,y,d) = f(x,y,d) + IND81 \bullet f(x,y,d) + IND89 \bullet f(x,y,d) + \varepsilon(x,y,d) \tag{7}$$

Model 4. Both height and shape are different (full model).

$$NO3(x,y,d) = IND81 + IND89 + f(x,y,d) + IND81 \bullet f(x,y,d) + IND89 \bullet f(x,y,d) + \varepsilon(x,y,d) \tag{8}$$

Using the same F test given by Equation (3), the following pairwise comparisons of the four models will be performed:

1. Model 4, or full model, vs. Model 1: testing for difference among the surfaces in terms of height and/or shape. If the test reveals significant difference between the two models, go to next two steps.

2. Model 4 vs. Model 3: testing for difference in height without assuming the same shape.

3. Model 4 vs. Model 2: testing for difference in shape without assuming the same height.

4. Model 2 vs. Model 1: testing for difference in height while assuming the same shape. If test 3 does not result in a significant difference, the conclusion from this test will be equivalent to that from test 2.

5. Model 3 vs. Model 1: testing for difference in shape while assuming the same height. If test 2 does not result in a significant difference, the conclusion from this test will be equivalent to that from test 3.

These pairwise comparisons will answer the following questions: (1) Is there any change in the spatial distribution of nitrate from year to year? (2) If the answer to (1) is positive, then what is the change? Is it the shape, or height, or both that have changed over years? Changes in the shape of the trend surface correspond to the changes in large-scale spatial distribution of nitrate in ground water, while changes in the height of surfaces represent the changes in the over-all magnitude of nitrate concentration in the basin. As such, comparison of nitrate surfaces will determine whether the magnitude and/or large-scale spatial variation of nitrate distribution in ground water have changed over years.

ANALYSES AND RESULTS

Examination of scatter plots of nitrate data shows that the observation from a single well stands out above the rest of data. The NO_3-N concentration in that well is 62.2, 51.1, and 47.8 mg/L for 1981, 1989, and 1992, respectively. These values are abnormally high compared with the corresponding annual means and medians as well as the values of other wells (Table 1). Hence, it is a suspicious outlier. The same descriptive statistics for NO_3-N data for the remaining 70 wells, after removing the outlier, are given in Table 2.

TABLE 1. Descriptive Statistics for NO_3-N (mg/L) in 71 Wells in the Basin.

Year	Mean	Median	Standard Deviation
1981	8.8	7.6	9.0
1989	5.7	4.2	7.3
1992	10.0	8.4	9.5

TABLE 2. Descriptive Statistics for NO_3-N (mg/L) in 70 Wells in the Basin (eliminating one well affected by point source problem).

Year	Mean	Median	Standard Deviation
1981	8.1	7.4	6.3
1989	5.1	4.2	4.8
1992	9.5	8.3	8.4

By comparing the two tables, it is obvious that the suspected outlier has a profound impact on the data. With this well dropped out, the standard deviations were reduced by 30 percent, 34 percent, and 12 percent for 1981, 1989, and 1992, respectively. In general, the effect of deleting a single large-valued observation on the estimate of the mean is linear, and on the standard deviation it is approximately quadratic. The standard deviation is much more sensitive to the magnitude of the deleted observation than the mean (Rajagopal, 1988).

The field records for the well site have suggested that the very high nitrate concentrations are likely caused by a point source instead of non-point sources (the well is located in a cattle feed lot). Since this study investigates the impact of non-point source pollution, data from this well was not used for the subsequent analyses.

As described in the previous section on methods, the large-scale variation in nitrate spatial distribution can be described as a surface over the basin. We assume that the surface can be specified as a polynomial function of spatial coordinates of well locations and well depths.

To compare two polynomial functions, first of all, we need to know if the two functions have the same order. Determination of the order of polynomial functions involves pairwise comparisons, which actually are a process of hypothesis testing (each function for a hypothesis). For a valid test, the error term in the function needs to satisfy some assumptions. Usually, residuals from fitting the model are examined for any violation of the assumptions. In this study, residuals

were analyzed with residual plots and semivariogram plots.

First, the residuals from fitting a linear polynomial function were plotted and examined. The residual plots showed some evidence of heteroskedasticity, i.e. non-constant variances. A log-transformation of the data was performed to stabilize the variance.

The semivariogram of residuals from fitting a linear polynomial function was then estimated using Cressie and Hawkins' more robust estimator (Cressie, 1993). The estimation was performed with SAS/IML software, which is part of the SAS system and especially designed for matrix programming (SAS, 1990).

The estimated semivariograms for the three sampling years appeared approximately as horizontal lines. This pure-nugget form of semivariogram plot is an indication that there is no significant spatial dependence among the observations at the scale of sampling.

Determination of the Order of Polynomial Functions

Detailed description of the testing process for determination of order of polynomial functions is given here only for year 1981, although the same procedure was performed for 1989 and 1992 also. Model fitting was carried out with the SAS procedure PROC GLM (General Linear Model) (SAS, 1989).

First, a linear (first-order) polynomial function was fit to the data; results are given in Table 3. As the P-value shows, the linear polynomial function is significant. A quadratic polynomial function was then fit to the data. The results are shown in Table 4.

To compare these two models, the following F statistic was calculated based on the formula (3),

$$\frac{(67.51-53.85)/(60-54)}{1.00}=2.28$$

Since the same F test (linear vs. quadratic) actually was performed three times (for three years), the Bonferroni correction was used, i.e. dividing the experimentwise level of significance by the number of comparisons. If we want the overall level of significance to be $\alpha = 0.05$, the level of significance for each comparison would be 0.05/3=0.017.

The tabled value, $F_{(0.017;6,54)} = 2.86$, was obtained using the MINITAB command INVCDF (Minitab, 1989). Since the calculated statistic, 2.28, is smaller than 2.86, the critical value for the given F distribution and significance level, no significant difference was found between the linear and quadratic polynomial functions. As a result, a linear polynomial function was chosen for the data for 1981.

The same procedure was applied to the data of the other two years. These tests show that the polynomial functions for nitrate concentration have the same order for all three sampling years, that is, the first order, or linear.

It is worth noting that because there are no well depth values for six wells in the record, the actual number of wells used in the analysis is 64 instead of 70. As a result, the total degrees of freedom in Tables 3 and 4 equal 63 rather than 69. Similarly, the total degrees of freedom in Tables 5 to 8 are 191 instead of 209 as they would be if all 70 wells were used in the analysis.

TABLE 3. ANOVA Table for the Linear Polynomial Function for 1981.

Source	DF	SS	MS	F Value	P-Value
Model	3	12.23	4.08	3.62	0.0180
Error	60	67.51	1.13		
Total	63	79.74			

Note: DF: degree of freedom; SS: sum of squares; MS: mean squares; Total: corrected total; P-Value: Pr > F.

TABLE 4. ANOVA Table for the Quadratic Polynomial Function for 1981.

Source	DF	SS	MS	F Value	P-Value
Model	9	25.89	2.88	2.88	0.0074
Error	54	53.85	1.00		
Total	63	79.74			

Note: DF: degree of freedom; SS: sum of squares; MS: mean squares; Total: corrected total; P-Value: Pr > F.

TABLE 5. ANOVA Table for the First Model (Equation 5); Assumes No Difference Among the Three Surfaces.

Source	DF	SS	MS	F Value	P-Value
Model	3	37.08	12.36	10.82	0.0001
Error	188	214.75	1.14		
Total	191	251.83			

Note: DF: degree of freedom; SS: sum of squares; MS: mean squares; Total: corrected total; P-Value: Pr > F.

TABLE 6. ANOVA Table for the Second Model (Equation 6); Assumes Only the Height of Surfaces is Different.

Source	DF	SS	MS	F Value	P-Value
Model	5	56.82	11.36	10.84	0.0001
Error	186	195.01	1.05		
Total	191	251.83			

Note: DF: degree of freedom; SS: sum of squares; MS: mean squares; Total: corrected total; P-Value: Pr > F.

TABLE 7. ANOVA Table for the Third Model (Equation 7); Assumes Only the Shape of Surfaces is Different.

Source	DF	SS	MS	F Value	P-Value
Model	9	43.22	4.80	4.19	0.0001
Error	182	208.61	1.15		
Total	191	251.83			

Note: DF: degree of freedom; SS: sum of squares; MS: mean squares; Total: corrected total; P-Value: Pr > F.

TABLE 8. ANOVA Table for the Full Model (Equation 8); Assumes Both the Height and Shape of Surfaces Are Different.

Source	DF	SS	MS	F Value	P-Value
Model	11	62.83	5.71	5.44	0.0001
Error	180	189.00	1.05		
Total	191	251.83			

Note: DF: degree of freedom; SS: sum of squares; MS: mean squares; Total: corrected total; P-Value: Pr > F.

Test for Difference in Spatial Surfaces

The spatial distribution of nitrate in the basin can be described by its overall magnitude and variation over space, equivalent to geometrically describing a nitrate surface by its height and shape. Hence, to explore changes in spatial distribution of nitrate from year to year, the nitrate surface can be tested for change over years in terms of its height and shape. Now that the first order polynomial function, i.e., a plane in three dimensions, was found to be appropriate for the nitrate surface, the test for change in surface shape became a test for change in the slope of the plane. The term slope is an extension from one- and two-dimensions; it cannot actually be drawn in three or higher dimensions.

As described previously, to test for changes in the nitrate surfaces, one full model and three reduced (or restricted) models were posited and fit to the combined nitrate data of all three years, distinguished by two indicator variables, ID81 and ID89 (Equations 5-8).

Variances of nitrate data were not the same from year to year. This was shown by the standard deviations in Table 2. Because of this, the weighted least squares method was used in the model fitting procedure, with the reciprocal of variances of residuals as weights. Model fitting was carried out with the SAS procedure PROC GLM. The results from fitting the above four models are shown in Tables 5-8.

Pairwise comparisons of the four models were carried out in the same fashion as in determining the order of polynomial functions, that is, using an F test for the difference in residual sum of squares adjusted for degrees of freedom between the two models under consideration. The sample F statistics were calculated using the formula (3). The results are shown in Table 9.

The last column of Table 9 lists the results of pairwise comparisons, in summary they show:

a - significant difference among the surfaces in terms of height and/or slope;

b - significant difference in height without assuming the same slope;

c - non-significant difference in slope without assuming the same height;

d - significant difference in height with slope being held the same;

e - nonsignificant difference in slope with height being held the same.

The pairwise comparisons show that significant differences exist among the three nitrate surfaces (test **a**). The main difference lies in the height of the surfaces (tests **b** and **d**). No evidence was found for significant differences in the slope of the nitrate surfaces (tests **c** and **e**).

The significant change in the surface height from year to year reflects the change in magnitude of nitrate concentration. As shown in Table 10, the annual change in nitrate concentration is coincident with climatic changes, especially in precipitation. The wettest year (1992) among the three sampling years had the highest nitrate concentration and the driest year (1989) had the lowest. It is also worth noting that water year 1989 followed an even drier year of 1988 with an annual precipitation of 582.8 mm; while water year 1992 was preceded by an even wetter year (1991) with an annual precipitation of 1200.9 mm. These situations further exacerbated the dry and wet conditions, respectively.

TABLE 10. Total Annual Precipitation and Mean NO_3-N Concentration (basin averages of the 70 wells).

	1981	1989	1992
NO_3-N (mg/L)	8.1	5.1	9.5
Precipitation (mm)	895.9	617.9	907.8

Note: Precipitation is the annual sum for the water year (from October 1 of the previous year to September 30 of the current year).

TABLE 9. Test for Differences Among Nitrate Surfaces of Three Sampling Years.

Model Comparison	F Statistic	F	
Models 4 vs. 1	$\frac{(214.75-189.00)/(188-180)}{1.05} = 3.07$	1.99	a
Models 4 vs. 3	$\frac{(208.61-189.00)/(182-180)}{1.05} = 9.34$	3.05	b
Models 4 vs. 2	$\frac{(195.01-189.00)/(186-180)}{1.05} = 0.95$	2.15	c
Models 2 vs. 1	$\frac{(214.75-195.01)/(188-186)}{1.05} = 9.40$	3.04	d
Models 3 vs. 1	$\frac{(214.75-208.61)/(188-182)}{1.15} = 0.89$	2.15	e

Note: F is the tabled value for the F distribution with given degrees of freedom. The level of significance is 0.05. **a, b, c, d, e:** discussion in the text.

CONCLUSIONS

Some observations can be made from the results of the data analyses:

1. The primary contribution to spatial variation in nitrate concentration comes from coordinates of the east-west direction (Figure 2). The increase in nitrate concentration from west to east in the basin constitutes the general pattern of the nitrate spatial distribution. In the westernmost part of the basin, the Galena aquifer becomes confined; protected from surficial inputs and direct recharge. Hence, nitrate concentrations are very low, often nondetectable, providing a gradient to greater concentrations in the unconfined areas to the east.

2. Nitrate surface did not show significant change in terms of its shape from 1981 to 1992. That is, the general pattern of spatial distribution of nitrate in the basin did not significantly change during the period of study.

3. The overall magnitude of nitrate concentration in the basin, or height of the computed surfaces showed significant fluctuation in the same period. Changes in magnitude were neither a monotonic increase nor a consistent decrease.

4. The change in magnitude of nitrate concentration over years follows the pattern of climatic variations, especially in precipitation. Nitrate leaching and movement in ground water are greatly enhanced by water flux (e.g., Hallberg, 1989; Hallberg and Keeney, 1993). The variations in precipitation likely are the major cause of the significant differences in nitrate concentration from year to year. A detailed study on the impact of climate on nitrate dynamics in ground water in the basin is given in Liu *et al.* (1997).

5. Changes in shape of nitrate surfaces are considered to be primarily caused by the change in spatial pattern of land use and management practices affecting nitrogen input. Through the Big Spring basin project, basin farmers have reduced nitrogen fertilizer rates on corn by 30 percent since the early 1980s, reducing environmental loading. However, the possible impacts of this improved land use and nitrogen management did not emerge from the spatial statistical analysis. This may mean that the influence of climatic-precipitation variations overshadowed the influence of land use and management practices. It may also mean that changes in land use and management did not occur in a systematic fashion, but instead happened randomly over the basin. As such, the changes in land use and management practices may have influence on nitrate concentration only on a small and local scale, but not on the overall trend of the spatial distribution.

6. The method described in this paper is not limited to the studies in nitrate contamination in ground

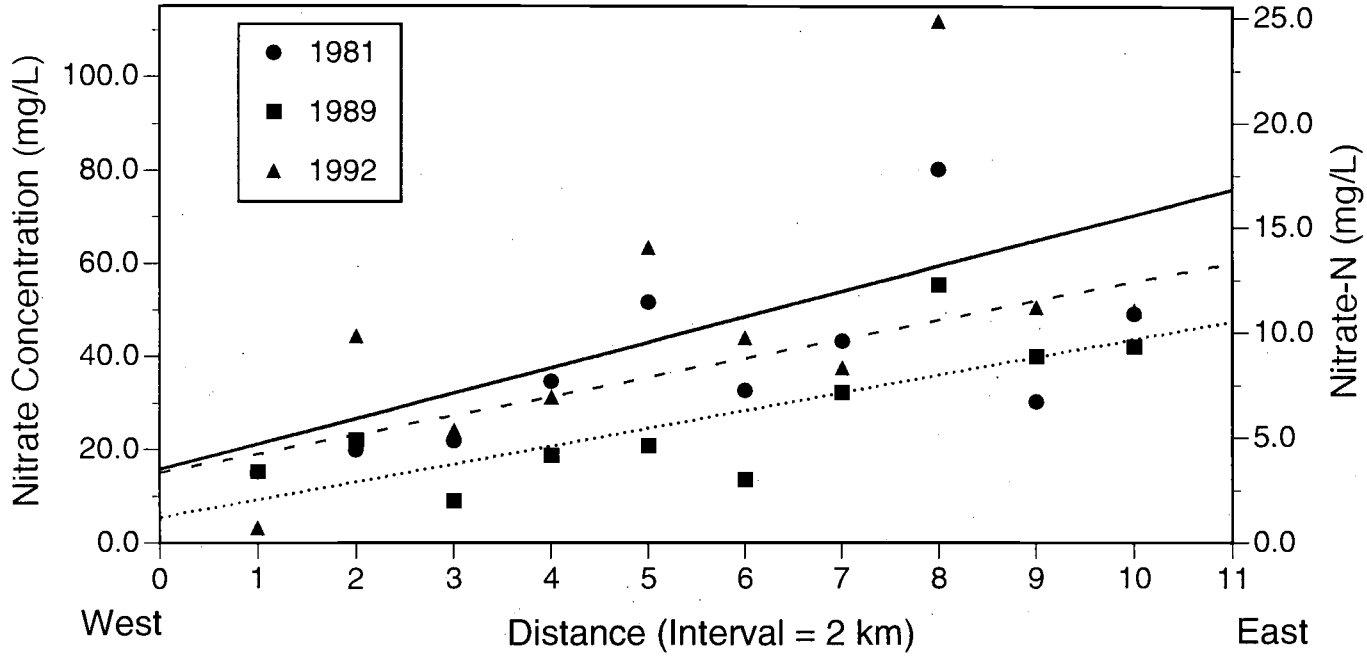

Figure 2. Changes in Nitrate Concentration from West to East in the Big Spring Basin. Each data point is the average nitrate concentration of water samples within a 2-km interval of distance in the W-E direction for a given year. Also in the figure are least-square fitting lines: lower dotted line for 1989; middle dashed line for 1981; and upper solid line for 1992.

water. It can also be used for analysis of large-scale spatial distributions in other studies.

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