A GIS-Based Statistical Method to Analyze Spatial Change

Joel D. Schlagel and Carlton M. Newton

Abstract
A GIS-based statistical method to examine spatial change was developed and demonstrated. Each measurement occasion is mapped as a separate GIS coverage. Then, using a raster GIS, a nonparametric test for trend is performed on a per-pixel basis across the collection of coverages. The spatial component of the data set is maintained, allowing further spatial analysis of the derived coverage.

The method was applied to a subset of the animal waste management data collected as part of the St. Albans Bay, Vermont, Rural Clean Water Project. It was found that from 1983 to 1990, significant increases ($P \leq 0.10$) in the rate of animal waste disposal occurred on 18 percent of the land within 100 metres of Jewett Brook, while significant decreases in application rate occurred on just 3 percent of the riparian land. This suggests that, despite widespread adoption of agricultural best management practices, agricultural activity was, to some extent, working against an improvement in water quality.

Introduction
Environmental research is frequently concerned with the measurement of variables whose magnitude and spatial distribution vary over time. Geographic information systems (GIS) are powerful tools for the analysis of such spatial changes (Johnson, 1990). Yet the ways in which GIS has been applied to the analysis of spatial change have been limited. Spatial change analysis with GIS is most commonly confined to the overlay of spatial data sets representing data at two points in time. Change is then represented as the difference of, or a ratio of, the two data sets (Lo and Shipman, 1990). Because only two data sets are used, the primary weakness of this method of change analysis is the inability to differentiate natural or random fluctuations over time from real trends.

This paper presents a GIS-based statistical method to examine spatial change. Given that the distribution and magnitude of a variable have been measured at evenly spaced time periods, each measurement occasion is mapped as a separate GIS coverage. Using a raster GIS, a nonparametric test is used to assess trend on a per-pixel basis, across the collection of these separate coverages (i.e., across the multitemporal data set).

Temporal Analysis Using GIS
When a multitemporal data set is of concern, mapping is often of limited value because it is difficult to visually interpret a map representing multitemporal data. Rather than present multitemporal data on a single map, the temporal dimension of the data is often summarized or eliminated. If the temporal dimension of a spatial database is to be summarized, that summarization should, in some way, assist in the interpretation of the data, so as to avoid basing conclusions about the spatial-temporal data set on non-significant or random variations (Choynowski, 1959). There are a variety of cartographic and computer-cartographic methods available to examine multitemporal spatial data.

The most common method of examining change is to overlay maps representing the spatial distribution of a variable of interest at two different time periods. This technique is widely used within both the raster GIS environment (Lo and Shipman, 1990) and the vector GIS environment (Ahern *et al.*, 1990). The overlay method is also used in image processing to construct temporal difference images, or temporal ratio images (Avery and Berlin, 1985). The results of the overlay of two coverages are easily represented on one map, and are easily interpreted visually. However, consideration of only two time periods may produce misleading or exaggerated results if there is any tendency of the variable of concern to cycle in either its spatial distribution, or in its magnitude. Cyclical variation may be incorrectly interpreted as either an upward or downward trend.

To overcome the limitations to understanding spatial change between two time periods, spatial data may be collected at multiple time periods. When data for multiple time periods are available for consideration, the meaningful use of overlay analysis becomes more difficult. A GIS may allow one to accurately overlay coverages representing data at many time periods, but a single map representing the results of the overlay of multiple coverages can be too complex to meaningfully interpret visually, so other techniques must be used.

One way to present a cartographic variable observed for multiple time periods is through the use of temporal "glyphs" (Monmonier, 1990). Temporal glyphs include bar charts or other complex symbols to portray change at a specific location. McCord and Olson (1989) apply this concept by developing a data transfer method between Arc/Info (ESRI, 1990) and SAS-Graph (SAS Institute, 1985), allowing graphs generated by SAS to be used as symbols in an Arc/Info map. When using the temporal glyph or graph-in-map method, much of the data may be redundant, or may not describe meaningful change. Furthermore, the large amount of data that are presented as one map may overwhelm the map reader, hindering understanding (VonEssen and Walsh, 1989).

Computer animation is another way of presenting a multitemporal data set so as to portray change. Computer anima-

---

School of Natural Resources, The University of Vermont, Burlington, VT 05405-0088.

J.D. Schlagel is presently with the Remote Sensing/GIS Center, U.S. Army Cold Regions Research and Engineering Lab., Hanover, MA 03755.

Photogrammetric Engineering & Remote Sensing,
Vol. 62, No. 7, July 1996, pp. 839–844.

0099-1112/96/6207–844$3.00/0

tion methods allow one to visualize change in a spatial data set over time as maps are displayed sequentially on a computer screen (MacEachren and DiBiase, 1991). While useful for many purposes, such a computer "flip book" does not assist in the quantification or the objective evaluation of spatial change. A more advanced conceptual approach to the problem of analyzing spatial change is to incorporate temporal-topology in a GIS, making temporal relationships as much a part of the data set as spatial relationships (Langran and Chrisman, 1990). Temporal topology does not, however, directly address the problem of quantification and representation of spatial change on a map.

An alternative to representing data measured at numerous time periods on a map is to statistically summarize the temporal data set. Descriptive statistics of a spatial data set could then be more easily presented and interpreted visually. Maps of descriptive statistics of the data set, such as the maximum, mean, or median values, could then be generated. However, maps of descriptive statistics can oversimplify or overgeneralize multitemporal data, reducing their usefulness (VonEssen and Walsh, 1989). Furthermore, descriptive statistics do not help one understand trends that may occur over time.

An improvement over the use of static descriptive statistics is the use of inferential statistics and hypothesis testing. For instance, the statistical hypothesis of no change may be tested throughout a study area, and the resulting statistics may be presented as a map. The mapping of the results of statistical analysis is common. This is demonstrated in Taylor and Loftis (1977) and Robinson *et al.* (1985). Both references demonstrate the mapping of predicted values and residuals from regression analysis, allowing one to consider the spatial relationships associated with the fit of a regression model.

If one wishes to explore statistically the relationship among GIS coverages, then the GIS data sets may be linked with other programs that possess more advanced statistical capabilities. For instance, image processing systems may be used to conduct principal components analysis of a raster based spatial data set. Principal components analysis of multitemporal spatial data sets has been used to reduce data redundancy and identify critical time periods (VonEssen and Walsh, 1989). Alternatively, one may transfer data from a series of GIS coverages to statistical packages, in order to conduct regression analysis among coverages (Ludeke *et al.*, 1990).

Rather than mapping the results of statistical analysis, one may perform the statistical analysis with the GIS. A raster GIS that is capable of mathematical overlay, or map algebra functionality as described by Tomlin (1990), can be used to perform most calculations needed for statistical tests. The use of a statistical test is one way of summarizing several temporal coverages in a form which may be easily presented visually, and provides a way to objectively view patterns of spatial change.

A Spatial Change Methodology

The null hypothesis that no trend exists in a single variable measured at multiple locations over time can be tested statistically using the overlay operations common to geographic information systems. Such a hypothesis may be tested within the vector GIS environment if comprehensive multitemporal data exist on a feature basis. However, the use of a raster GIS procedure to analyze multitemporal data is preferable if polygon identifications or boundaries change over time. The use of a raster GIS allows the consideration of the trend at a specific location regardless of change in its identification or group boundary.

A variable measured in geographic space may be spatially continuous or spatially discrete. The transition between locations may be smooth or abrupt (MacEachren and DiBiase, 1991). These characteristics of a spatial distribution affect both the ways in which the variable may be represented, and the types of spatial analysis techniques that may be used to study the distribution. The use of a raster-overlay method to statistically analyze spatial change is applicable whether the variable of concern is spatially continuous or spatially discrete, and whether changes are smooth or abrupt.

A variety of statistical tools are available to examine the existence of trend. The most common method is simple linear regression. The standard use of linear regression, a parametric statistical technique, requires independent random samples drawn from normally distributed populations (Taylor, 1977). These requirements may not be met in a spatial data set where systematic sampling or total enumeration has been conducted, or if the statistical distribution of the data is non-normal. Under these conditions, the use of a distribution-free or non-parametric statistical test may be appropriate. In particular, a rank test may be useful within a cartographic environment where categorical data are often collected.

The Mann-Kendall test is a nonparametric test for zero slope of the linear regression of time-ordered data versus time (Gilbert, 1987). It is an application of Kendall's rank order correlation test to time series data (Bradley, 1968). The Mann-Kendall test is appropriate for trends in time series data when the data may have a skewed distribution, may contain missing values, may have values below specified detection limits, or spatial and temporal correlation may exist among data (Taylor and Loftis, 1989; Lettenmaier, 1988). The insensitivity of the Mann-Kendall test to lack of normality is important, both because of the potential for small sample sizes, and because it is impractical to normalize the data for each pixel location individually. Gilbert (1987) presents the following procedure to calculate the Mann-Kendall trend statistic:

(1) List the data in the order in which they were collected over time:

$$x_1, x_2, \ldots, x_n \text{ where } x_i \text{ is the datum at time } i.$$

(2) Determine the sign of all $n(n-1)/2$ possible differences of $x_j - x_k$ where $j > k$. Let $\mathrm{sgn}(x_j - x_k)$ be an indicator function that takes on the value of 1, 0, or −1 according to the sign of $x_j - x_k$:

$$\mathrm{sgn}\,(x_j - x_k) = \quad +1 \quad \text{if } x_j - x_k \; 0$$

$$\mathrm{sgn}\,(x_j - x_k) = \quad 0 \quad \text{if } x_j - x_k = 0$$

$$\mathrm{sgn}\,(x_j - x_k) = \quad -1 \quad \text{if } x_j - x_k \; 0$$

(3) Compute the Mann-Kendall Statistic:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \mathrm{sgn}\,(x_j - x_k)$$

(4) Compare the value obtained with a tabled critical value for a selected level of significance.

(5) Reject the hypothesis of no trend if $|S|$ is larger than the tabulated value, and retain the hypothesis of no trend if $|S|$ is smaller than the tabulated value.

In this case, the Mann-Kendall trend statistic is calculated for each pixel location in a time series of raster GIS coverages. To prepare the data, calculate a difference coverage for all pairs of coverages, subtracting the earlier time period from the later time period. For example, if one were considering four time periods, six overlay operations would be performed, resulting in six new coverages: Time 2 minus Time 1, Time 3 minus Time 1, Time 4 minus Time 1, Time 3 minus Time 2, Time 4 minus Time 2, and Time 4 minus Time 3. Each difference coverage is then reclassified twice. The

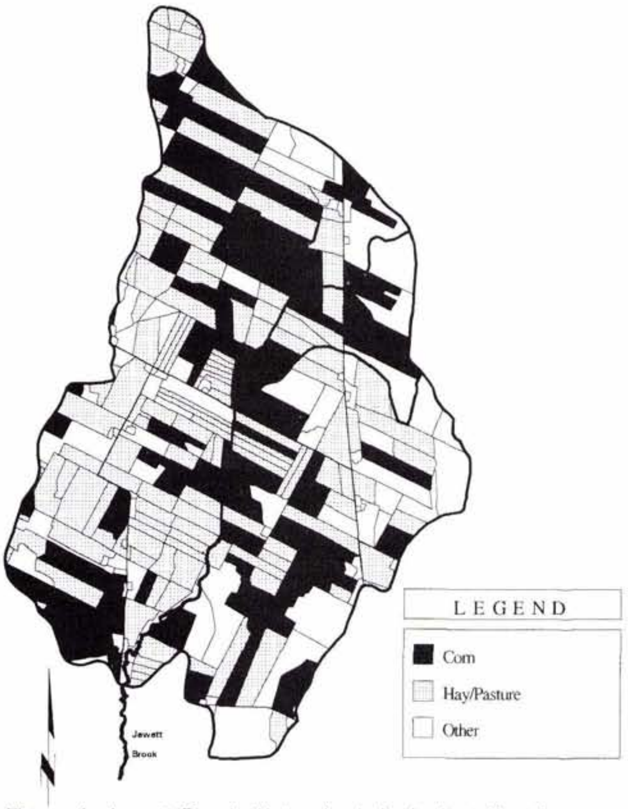

Figure 1. Jewett Brook Watershed: Agricultural land use, 1990.

first reclassification generates a binary coverage containing the value +1 for all positive values in the difference coverage, and zero for all other values in the coverage. The second reclassified coverage contains the value of −1 for all negative values of the subtraction, and zero for all other values. Addition overlay is then used to sum the binary coverages for positive and negative values separately, yielding coverages containing the total of negative values and the total of positive values. A difference overlay is then effectively performed by adding the coverage containing the negative total to the coverage containing the positive total. The result is a single coverage containing the Mann-Kendall trend statistic. A new coverage containing probability values is then generated using a look-up table of critical values (see Hollander and Wolfe (1973) or Gilbert (1987) for probability values of the Mann-Kendall trend for trend). Finally, the data are reclassified in order to indicate the test result for the hypothesis of no significant trend, at a given level of significance.

Any trend analysis involving multiple coverages has to contend with the potential for misregistration. If misregistration occurs, it is possible that change will be indicated where none occurred, or vice versa. This can be a particular problem if the coverages and the comparative computations are done on a pixel-by-pixel basis.

There are two general types of misregistration that should be anticipated. One type of registration error occurs when one or more of the coverages do not represent exactly the same geographic area. The chance of this happening is minimized by using the same map projection and map origin for each coverage. Operationally, this can be accomplished by using a common base map, or template, when building each coverage. However, if the coverages are imported from elsewhere, the use of a common control network will help reduce the extent of misregistration among coverages.

The second major form of misregistration results when boundaries designating different land-use or ownership polygons are not accurately known or mapped. Pixels in the vicinity of such boundaries are particularly subject to the indication of change when in fact there is none. To reduce the potential magnitude of this type of problem, it is important to first start with careful data collection methods, mapping boundaries as accurately as possible. Then, a pixel size should be selected that is appropriate for the locational accuracy of the data. It should be noted that, if the boundary locational errors are random, the resulting false indications of change will tend to mask the existence of any trends.

The analyst can never be assured that all forms of misregistration have been eliminated. But if it does exist, a strength of the pixel-by-pixel use of the Mann-Kendall trend statistic is that any changes must be relatively consistent if a significant trend is to be indicated.

Application of the Spatial Change Methodology

The spatial trend methodology was applied to a subset of the land-use data collected by the St. Albans Bay Rural Clean Water Program (RCWP) from 1983 through 1990. The St. Albans Bay watershed is located in northwestern Vermont, 40 km north of Burlington. The watershed drains 13,000 hectares of agricultural, forested, and urban land into St. Albans Bay of Lake Champlain. St. Albans Bay has been experiencing accelerated eutrophication due to the input of nutrients from both point and non-point sources. The most significant nonpoint source of pollution in the St. Albans Bay was believed to be surface runoff from dairy farms (VTRCWPCC, 1991).

The Jewett Brook watershed is an area of 1,384 hectares at the north end of the St. Albans Bay watershed, representing slightly less than 11 percent of the total watershed area. Approximately 85 percent of the land within the Jewett Brook watershed is presently in agricultural use by 21 dairy farms (see Figure 1). The remaining land is generally woodland or residential.

As part of the St. Albans Bay RCWP, an intensive land-use and water quality monitoring program was conducted by the University of Vermont Water Resources Research Center. The results of the water quality monitoring program suggested that implementation of the recommended agricultural management practices in the Jewett Brook Watershed did not result in significantly improved water quality over the monitoring period (VTRCWPCC, 1991; Meals, 1992a). The spatial trend methodology was applied to the Jewett Brook watershed animal waste management data in order to investigate whether changes in the spatial pattern of animal waste application occurred over time, and if these changes could in some way have offset the anticipated benefits from implementing the recommended agricultural management practices.

Data and Methods

Agricultural land-use monitoring of the Jewett Brook Watershed began in 1983. A map of the watershed identifying each farm and field was prepared from 1:5,000-scale orthophotographs. A vector GIS was used to store farm and field boundaries, land use, and land ownership. The coverage containing land-use and land-ownership data was updated annually from 1983 through 1990 to account for crop rotation and fields being split, combined, or sold. A tabular database contained more detailed information on agricultural activity, including planting and harvesting dates, number and type of farm animals, and, most importantly for our research, the date, method, and amount of manure applied on a farm field. Farmers in the watershed served as the primary source of data for the monitoring program. Information collected from farmers resulted in a database of agricultural activity on a field by field basis, and eight annual land-use coverages. This database served as the input for the spatial trend analysis.

The spatial trend methodology required that all locations have data values for all time periods. However, data for one or two farms for each year were usually missing. Missing data generally accounted for 1 or 2 percent of the land area in a given year, and was always less than 6 percent of the land area. In these cases, missing data values were replaced with data from the previous year; thus, the assumption was that, if no data were available, the farmer did the same thing as in the previous year.

Manure application data were aggregated to an annual total for each farm field. The annual total was converted to a rate in tons per acre and added to the vector GIS coverage containing the appropriate farm and field boundaries. These vector coverages were then converted to raster coverages, with each pixel representing an area of 256 square metres. The raster coverage was then transferred to the raster geographic information system, which was used to conduct the spatial trend analysis. The resulting Mann-Kendall trend coverage was then transferred from the raster system back to the vector system for display, overlay analysis, and final map preparation.

Results

Figures 2a and 2b represent the results of the analyses of trend in annual manure application rate in the Jewett Brook watershed. Shading indicates the presence of an upward or downward trend at the $P \leq 0.20$ (Figure 2a) and $P \leq 0.10$ (Figure 2b) significance levels. The inclusion of the $P \leq 0.20$ level was considered important for this data set because of the small sample size ($n=8$ years). Shading also indicates those regions that received manure during the project, but for which there was no significant trend, and those regions that did not receive manure during the project period.

The intensity of agricultural practice in the watershed is evident in Figures 2a and 2b. Seventy-two percent of the total watershed area was used for animal waste disposal at some time during the project period. As presented in Table 1, statistically significant decreases in manure application rates occurred on 41 hectares at $P \leq 0.10$ and an additional 39 hectares at a significance level between $P \leq 0.10$ and $P \leq 0.20$, for a total of 80 hectares at $P \leq 0.2$. Significant increases in manure application rates occurred on 129 hectares at $P \leq 0.10$ or 294 hectares at a significance level of $P \leq 0.20$. No statistically significant trend was observed on 621 hectares at $P \leq 0.20$.

TABLE 1. TREND IN ANNUAL MANURE APPLICATION RATES

Direction of Trend	Watershed Land (Ha)	Watershed Land (%)	Manured Land (%)
Downward Trend $P \leq 0.10$	41	3.0	4.0
Downward Trend $P \leq 0.20$	80	5.8	8.0
No Trend $P \leq 0.10$	826	59.7	83.0
No Trend $P \leq 0.20$	621	44.9	62.4
Upward Trend $P \leq 0.10$	129	9.3	13.0
Upward Trend $P \leq 0.20$	294	21.4	29.6
Total Manured Area	996	72.0	100.0
Non-Manured Area	389	28.1	—
Total Watershed Area	1,384	100.0	—

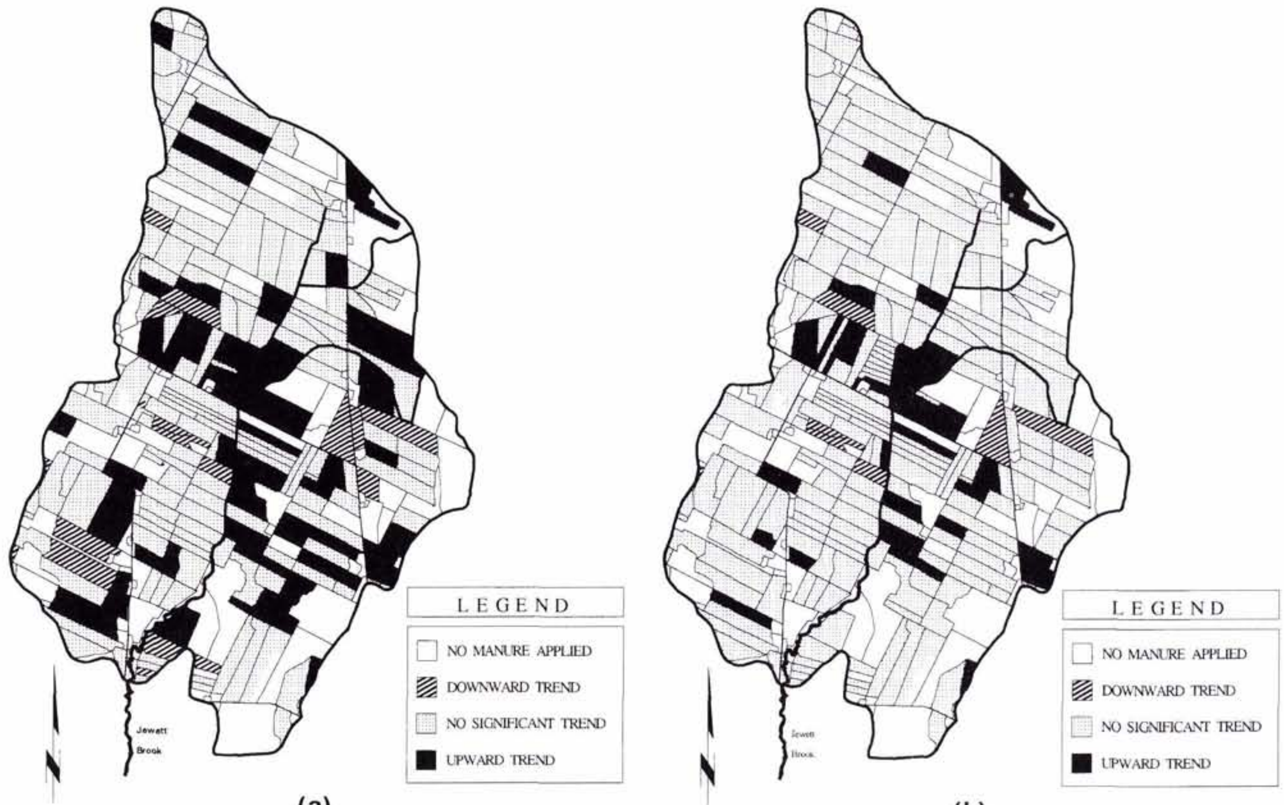

Figure 2. (a) Jewett Brook watershed 1983–1990: Trend in annual manure application rate ($P<0.20$). (b) Jewett Brook watershed 1983–1990: Trend in annual manure application rate ($P<0.10$).

TABLE 2. TREND IN ANNUAL MANURE APPLICATION RATE VERSUS DISTANCE TO JEWETT BROOK

Direction of Trend And Significance	Distance to Jewett Brook (Metres) 50	100	200	500	WS*
	hectares (percent)				
Downward Trend P≤0.10	2 (2.4)	4 (3.0)	10 (3.9)	23 (4.8)	40 (4.0)
Downward Trend P≤0.20	2 (3.8)	6 (4.7)	14 (5.7)	34 (7.0)	80 (8.0)
No Trend P≤0.10	52 (77.9)	105 (78.8)	199 (80.3)	386 (79.7)	824 (83.0)
No Trend P≤0.20	40 (60.5)	79 (59.5)	144 (58.1)	285 (58.9)	620 (62.4)
Upward Trend P≤0.10	13 (19.7)	24 (18.2)	39 (15.8)	75 (15.5)	129 (13.0)
Upward Trend P≤0.20	24 (35.7)	48 (35.9)	90 (36.2)	165 (34.1)	294 (29.6)
Mon-Manured Area	22 (24.4)	40 (23.3)	73 (22.7)	171 (26.1)	387 (28.0)
Total Buffered Area	89 (100)	172 (100)	321 (100)	655 (100)	1384 (100)

*WS = Total Watershed Area

When land not used for animal waste management is eliminated from consideration, one finds that significant increases (P≤0.10) in manure application rate occurred on 13.0 percent of the land that was used for animal waste disposal during the project period, and 29.6 percent of waste management land showed an increase at a significance level of P≤0.20. Significant decreases (P≤0.10) occurred on only 4.0 percent of the land used for animal waste disposal, with 8.0 percent of the waste disposal land indicating a decrease at a significance level of P≤0.20.

The analysis of the spatial data set summarized the temporal dimension of the data, while preserving the spatial component of the data, allowing further GIS analysis of the results of the statistical overlay operation. For instance, agricultural activity close to Jewett Brook has been found to be more highly correlated with changes in surface water quality than had agricultural practice at more remote locations (VTRCWPCC, 1991; Meals, 1992b). Thus, it is useful to consider trends in manure application rate with respect to location in the watershed.

To investigate whether changes in manure application rate tended to occur near Jewett Brook, or at more remote locations in the watershed, buffers around Jewett Brook were created at 50, 100, 200, and 500 metres. The buffer coverages were then overlaid with the Mann-Kendall trend coverage, with the results summarized in Table 2. Increases in manure application rate were found to have occurred more frequently on land within 100 metres of Jewett Brook as compared to the watershed as a whole, while decreases in application rate occurred less frequently within 100 metres of Jewett Brook. Within 50 metres and 100 metres of the stream course, annual manure application rate increased (P≤0.10) on 19.7 and 18.2 percent of the land, respectively, as compared to 13 percent of the land across the watershed. At P≤0.20, the increases in manure application occurred on 35.9 percent of the land within 100 metres of Jewett Brook, as compared to 29.6 percent across the watershed. Decreases (P≤0.10) in manure application rate occurred on 2.4 and 3.0 percent of the land within 50 and 100 metres of the stream course, as compared to 4.0 percent watershed wide.

A further analysis of the Mann-Kendall trend coverage was conducted to investigate whether trends in manure application rates were associated with particular farms. Though the initial analysis of trend in application rate deliberately ignored farm and field designations and boundaries because they varied over the course of the project, current farm boundaries could be used to investigate trends in animal waste management practice at the farm level. The coverage containing the annual Mann-Kendall result was intersected with the 1990 land ownership coverage. This revealed that one farm was responsible for increases in manure application rate on 38 hectares, or 29 percent of all acres, with a significant increase in application rate at p≤0.10. This farm is located in the center of the watershed at the junction of the two branches of Jewett Brook. A review of the field logs for the farm revealed that herd size consistently increased over the project period.

Discussion

By applying a statistical test for trend to manure application rate data, non-systematic or random variation in application rate from year to year, and the cyclical changes in application rate due to crop rotation, were filtered out, leaving only those fields with real trends in application rate for further consideration. Despite a sample size of only eight yearly coverages, statistically significant trends were observed at the P≤0.10 significance level. A large multitemporal spatial database was objectively and efficiently reduced to a smaller data set that could be easily interpreted in both visual and tabular format. Reduction of the multitemporal data to one coverage representing trend allowed the use of overlay analysis to examine spatial characteristics of the location of trend. This allowed identification of one farm as an important contributor to the increase in application rates, and allowed the location of significant changes in application rate within the watershed to be considered.

For the significance levels of the Mann-Kendall test to be statistically valid, the technique presented assumes that, for any given pixel, the different coverage values are independent. In the example presented, this assumption may be questioned because a farmer's activities on a field are arguably similar from one year to the next. However, the lack of independence does not invalidate the general procedure. Though the significance levels of the Mann-Kendall statistic are no longer tied directly to probability theory, they are very useful for identifying trends. Thus, the process, then, is useful for detecting and presenting the spatial arrangement of trends, except that now the classifications are not amenable to strict statistical interpretations.

This methodology as presented herein requires that each pixel location have the same number of data observations. In addition, because each pixel is examined independently, the variable for which trends are to be assessed must be standardized across all of the pixels, so that any trends presented will be comparable. Finally, the interpretation of the data can often be made more meaningful by viewing the trend map along with other statistical maps, such as maps of means and standard errors.

Conclusions

If spatial data collected over time are to be truly useful, the conclusions presented must be both objective and persuasive. A GIS-based method was presented to test for the existence of trends in a spatially distributed quantitative data set. The

Mann-Kendall trend statistic was calculated at each pixel location using overlay functions common to raster geographic information systems. Other statistical tests could be conducted in a similar manner. This type of analysis is an improvement over representation of change as either "percent change" or through some type of "index of change" because it assists in the objective analysis of the data set. The method presented is robust in that it can be applied irrespective of both statistical distribution (i.e., lack of normality) of the data and the spatial distribution of the data (discrete or continuous). It is also robust to changes in boundaries occurring over time.

The GIS-based statistical method was demonstrated using a subset of the land-use data collected as part of the St. Albans Bay Rural Clean Water Program. Assuming independence of the coverages, it was found that significant increases in annual manure application rates over time occurred on 20 percent of the land within 50 metres of Jewett Brook that received manure during the project period, compared with decreases on just 2 percent of the land within 50 metres of Jewett Brook ($P \leq 0.10$). Watershed wide, statistically significant increases in manure application rates occurred on 13 percent of the land receiving manure, and decreased on 4 percent of the land ($P \leq 0.10$). The observed increases in manure application rates, particularly on riparian land, demonstrates that agricultural practices occurring in the Jewett Brook watershed over the study period may have been working against improvements in water quality.

More generally, the existing numeric capabilities of a raster- or grid-based geographic information system can be used to statistically analyze the relationships between spatial data sets gathered over numerous time periods, and to identify spatial patterns associated with change. By using a statistical test value with known probabilities as a measure of change rather than generating an arbitrary index of change, the method presented facilitates an objective analysis of the spatial data set.

References

Ahern, J., J. Fabos, J. Mullin, and N. Lacour, 1990. Effectiveness of Land Use Controls for Protection of Water Quality in the Wachusett Reservoir, Massachusetts, *Proceedings of the 10th Annual ESRI User Conference, Volume II*, ESRI, Redlands, California.

Avery, T.E., and G.L. Berlin, 1985. *Interpretation of Areal Photographs*, Burgess Publishing, Minneapolis, 554 p.

Baker, J.L., and H.P. Johnson, 1983. Evaluating the Effectiveness of BMPs from Field Studies, *Agricultural Management and Water Quality* (F.W. Schaller and G.W. Bailey, editors), Iowa State University Press, Ames, pp. 281–304.

Bradley, J.V., 1968. *Distribution Free Statistical Tests*, Prentice Hall, Englewood Cliffs, 387 p.

Choynowski, M., 1959. Maps Based on Probabilities, *Spatial Analysis* (B.J. Berry and D.F. Marble, editors), Prentice Hall, Englewood Cliffs, pp. 180–183.

Eastman, J.R., 1990. *Idrisi Users Manual*, The Idrisi Project, Clark University, Worcester, Massachusetts.

Environmental Systems Research Institute, 1990. *Arc/Info Users Guide*, ESRI, Redlands, California.

Gilbert, R.O., 1987. *Statistical Methods for Environmental Pollution Monitoring*, Van Nostrand Reinhold, New York, 320 p.

Hollander, M., and D.A., Wolfe, 1973. *Nonparametric Statistical Methods*, Wiley, New York, 503 p.

Johnson, L.B., 1990. Analyzing Spatial and Temporal Phenomena Using Geographical Information Systems, A Review of Ecological Applications, *Landscape Ecology*, 4(1):31–43.

Langran, G., and N.R. Chrisman, 1988. A Framework for Temporal Geographic Information, *Cartographica*, 25(3):1–14.

Lettenmaier, D.P., 1988. Multivariate Nonparametric Tests for Trend in Water Quality, *Water Resources Bulletin*, 24(3):505–512.

Lo, C.P., and R.L. Shipman, 1990. A GIS Approach to Land-Use Change Dynamics Detection, *Photogrammetric Engineering & Remote Sensing*, 56(11):1483–1491.

Ludeke, K.M., R.C. Maggio, and L.M. Reid, 1990. An Analysis of Anthropogenic Deforestation Using Logistic Regression and GIS, *Journal of Environmental Management*, 31:247–259.

MacEachren, A.M., and D. DiBiase, 1991. Animated Maps of Aggregate Data: Conceptual and Practical Problems, *Cartography and Geographic Information Systems*, 18(4):221–229.

McCord, R.A., and R.J. Olson, 1989. New Dimensions from Statistical Graphics for GIS Analysis and Interpretation, *Proceedings of the 9th Annual ESRI User Conference*, ESRI, Redlands, California.

Meals, D.W., 1992a. Water Quality Trends in The St. Albans Bay, Vermont Watershed Following RCWP Land Treatment, *Proc. National RCWP Symposium*, September, Orlando, Florida.

———, 1992b. Relating Land Use and Water Quality in the St. Albans Bay Watershed, Vermont, *Proc. National RCWP Symposium*, September, Orlando, Florida.

Monmonier, M., 1990. Strategies for the Visualization of Geographic Time-Series Data, *Cartographica*, 27(1):30–45.

Nyerges, T.L., 1991. Analytical Map Use, *Cartography and Geographic Information Systems*, 18(1):11–22.

Robinson, A.H., R. Sale, and J. Morrison, 1978. *Elements of Cartography, 4th ed.*, John Wiley and Sons, New York, 448 p.

SAS Institute, 1985. *SAS Users Guide*, SAS Institute, Cary, North Carolina.

Taylor, C.H., and J.C. Loftis, 1989. Testing for Trend in Lake and Ground Water Quality Time Series, *Water Resources Bulletin*, 25(4):715–726.

Taylor, P.J., 1977. *Quantitative Methods in Geography*, Waveland Press, Prospect Heights, 386 p.

Tomlin, C.D., 1990. *Geographic Information Systems and Cartographic Modelling*, Prentice Hall, Englewood Cliffs, 249 p.

Vermont RCWP Coordinating Committee, 1991. *St. Albans Bay Rural Clean Water Program Final Report 1980–1990*, Vermont Water Resources Research Center, University of Vermont, Burlington, Vermont, 508 p.

VonEssen, I.E., and S.J. Walsh, 1989. Automated Approaches for Displaying Spatially Oriented Time-Series Data Through Image Processing Techniques, *Geocarto International*, 4:27–37.

(Received 2 August 1993; revised and accepted 1 June 1994; revised 8 December 1994)