United States
Environmental Protection
Agency

Environmental
Research Laboratory
Corvallis OR 97333

Research and Development

EPA/600/S3-89/037 Sept. 1989

EPA

Project Summary

An Evaluation of Trend Detection Techniques for Use in Water Quality Monitoring Programs

J.C. Loftis, R.C. Ward, R.D. Phillips, and C.H. Taylor

Goals for a long-term water quality monitoring program designed to measure the impacts of acid precipitation were identified using the Acid Precipitation Act of 1980 (PL 96-294, Title VII) as a basis. These goals were refined to obtain statistical hypotheses concerning trends in water quality that could be statistically tested.

Seven statistical tests were identified as capable of providing the desired information regarding trends in individual systems. The tests were evaluated under various conditions (distribution shape, seasonality, and serial correlation) in order to determine how well they might perform. A Monte Carlo simulation approach was used to evaluate the tests.

For annual sampling, the Kendall-tau test is recommended. For seasonal sampling, either the Seasonal Kendall test or the analysis of covariance (ANOCOV) on ranks test is recommended.

This Project Summary was developed by EPA's Environmental Research Laboratory, Corvallis, OR, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

One of the major goals of the Acid Precipitation Act of 1980 (PL 96-294, Title VII) is the evaluation of the environmental effects of acid precipitation. To accomplish this purpose, we must be able to detect trends in water quality related to acid precipitation and understand the nature of these trends.

In this report, the authors examine the statistical characteristics of the water quality variables most pertinent to acidification (ANC, pH, and SO_4^{2-}) and use these characteristics to estimate the ability of seven statistical tests to detect temporal trends of varying magnitudes. The report focuses strictly on populations of lakes and streams sensitive to acidification. It is concerned only with detecting trends over time and does not deal directly with cause and effect.

Trend Detection Tests—Description and Evaluation

The goal most relevant to detecting long-term trends is the estimation of regional trends in surface water acidification or recovery. Further refinement of this goal into a statistically meaningful statement around which a statistically sound monitoring system can be designed is required. This refinement involves stating the goal as a hypothesis that can be tested using the data as they are collected. The null hypothesis can be stated as: there are no long-term regional trends in the acidification or recovery of surface waters. The alternate hypothesis is that a trend exists.

The available tests for this null hypothesis were evaluated using a univariate time series approach. The single variable can be the concentration of a water quality constituent, the ratio of concentrations of two constituents, or the

weighted average of concentrations over a group of lakes or streams.

Statistical characteristics of concern are distribution shape (normality versus non-normality), seasonal variation, and serial correlation. There was no attempt to incorporate the effects of hydrologic variables such as rainfall or acidic deposition into recommended trend analysis procedures, although the usefulness of doing so is discussed.

In order to select statistical tests that are well matched to both the goals and anticipated data attributes, background data from several sources were studied. Data sources included the U.S. EPA's Long-term Monitoring (LTM) data set, data from Environment Canada for Clearwater Lake, Ontario, and data from the U.S. Bureau of Reclamation for Twin Lakes, Colorado. From these data, generalizations were made regarding the level of seasonal behavior, serial correlation, and non-normality to be anticipated.

Seven candidate tests for trend detection, including parametric and nonparametric approaches, were selected for evaluation. Several options for dealing with seasonality were included, and one test included a correction for serial correlation. The candidate trend tests were as follows:

- Analysis of covariance (ANOCOV)
- Modified "t"
- Kendall-tau, following removal of season means
- Seasonal Kendall with serial correlation correction
- Seasonal Kendall
- ANOCOV on ranks
- Modified "t" on ranks

The candidate tests were evaluated by comparing their performances under a Monte Carlo simulation study designed to reproduce the anticipated data characteristics. The performance indices were (1) actual significance level and (2) power of trend detection. Based on Monte Carlo results, a single trend test was selected for annual data and two tests are recommended for seasonal data.

Recommendations

For annual sampling, the recommended test is the Kendall-tau, also called the Mann-Kendall test for trend. The Mann-Kendall test is nonparametric and is a member of the class of tests called rank correlation methods, meaning that the test checks for a correlation between the ranks of data and time. The test does not account for seasonal variation. Since, however, it is recommended for use with annual data only, no prior removal of seasonal means is necessary.

For seasonal (generally quarterly) sampling, two alternative tests are recommended: (1) analysis of covariance (ANOCOV) on ranks or (2) the Seasonal Kendall test. Both tests are nonparametric and both tests performed very well under most of the conditions studied in the Monte Carlo analysis (i.e., seasonal variation and both non-normal and log-normal error).

Justification of Recommendations

The approach taken to compare alternate trend tests was to conduct a simulation of water quality variables under varying trend magnitudes and assumed behavioral characteristics. Recommendations were formulated based on a comparison of empirical significance levels and power of candidate tests.

Comparison of trend testing methods was achieved through Monte Carlo testing. In a Monte Carlo evaluation, the significance level of a test is determined by generating a large number of sequences of data with known characteristics and no trend. The test is applied to each sequence with the significance level being the fraction of trials in which a trend is falsely detected. The power of a given test is determined the same way, except that a trend of known magnitude is added to each synthetic data sequence. The power is then the fraction of sequences in which the trend is correctly detected.

A total of 3,024 simulations were conducted covering different ranges of seasonality, trend magnitude, underlying distribution, and serial correlation. Results showed that the most powerful tests over the range of conditions studied were the Seasonal Kendall test and ANOCOV on ranks, although as expected, no single test performed best under all conditions. Both of these tests performed as well as the parametric tests, when the data were normal, and both outperformed (were more powerful than) the parametric tests when the underlying distribution was log-normal. In a few cases, the Kendall-tau on deseasonalized data was more powerful, but it did not generally preserve the nominal significance level as well as the other tests. The modified "t" test on ranks performed well, but was in most cases slightly less powerful than ANOCOV on ranks. All tests, except the corrected Seasonal Kendall, suffered from inflated significance levels under serial correlation. The corrected test however, was much less powerful than the other tests, except for very large trend magnitudes and/or long data records.

Expected Performance of Monitoring--Power of Trend Detection

The actual ability of monitoring and data analysis to detect trends in water quality depends upon data characteristics, especially temporal variance and upon the shape or functional form and magnitude of the trend that actually occurs. Thus trend detection power cannot really be predicted in advance. It is informative, however, to assume a reasonable set of data characteristics and trend characteristics and then to calculate detectable trend magnitudes over various time horizons. The adequacy of a proposed monitoring network design can thus be evaluated in objective terms.

Theoretical curves depicting the power of trend detection for individual systems versus time for quarterly and annual sampling were constructed and compared to simulation results. Comparable curves were developed for multiple lakes for the problem of detecting changes in regional means. The Kendall and ANOCOV tests were also applied to historical data from Clearwater Lake, Ontario, and Twin Lakes, Colorado.

Specialized Procedures

Specialized techniques, in which the interrelationships among multiple water quality variables and/or local watershed conditions are considered, are likely to be more powerful for detecting trends. These techniques include adjustment for hydrologic factors, such as stream flow and precipitation, use of water quality indices, multivariate trend tests, and analysis of water quality or watershed model output. Possible implementation of these techniques is discussed in the report.

References

Conover, W. J. 1980. Nonparametric Statistics. Second Edition. John Wiley and Sons, New York.

Dietz, G. J. and T. J. Killeen. 1981. A nonparametric multivariate test for monotone trend with pharmaceutical applications. J. Am. Stat. Assn 76(373):169-174.

Dinius, S. H. 1987. Design of an index of water quality. Water Resources Bull. 23(5):833-843.

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

Hirsch, R. M. and E. J. Gilroy. 1985. Detectability of step trends in the rate of atmospheric deposition of sulfate. Water Resources Bull. 21(5):733-784.

Hirsch, R. M. and J. R. Slack. 1984. A nonparametric trend test for seasonal data with serial dependence. Water Resources Research. 20(6):727-732.

Hirsch, R. M., J. R. Slack, and P. A. Smith. 1982. Techniques of trend analysis for monthly water quality data. Water Resources Research. 18(1):107-121.

Hollander, M. and D. A. Wolfe. 1973. Nonparametric Statistical Methods. John Wiley, New York.

Kendall, M. G. 1975. Rank Correlation Methods. Fourth Edition. Charles Griffin, London.

Lettenmaier, D. P. 1976. Detection of trends in water quality data for records with dependent observations. Water Resources Research. 12:1037-1046.

Mann, H. B. 1945. Nonparametric tests against trend. Econometrica. 13:245-274.

National Research Council. 1977. Analytical studies for the Environmental Protection Agency: Vol. IV, Environmental Monitoring. Natl. Acad. Sci., Washington, D.C. (Library of Congress Catalog Card No. 77-86463).

Neter, W. E. and J. A. Wasserman. 1974. Applied Linear Statistical Models. Irwin, Inc., New York.

Newell, A. D., C. F. Powers, and S. J. Christie. 1987. Analysis of data from long-term monitoring of lakes. EPA600/4-87/014, U.S. EPA Environmental Research Laboratory, Corvallis, Oregon.

Newell, A. D. 1987. Personal communication. U.S. EPA Environmental Research Laboratory, Corvallis, Oregon. May.

Nicholls, A. 1987. Personal communication. Ministry of the Environment. Dorset, Ontario, Canada. July 31.

Sartoris, J. 1987. Personal communication. U.S. Department of Interior, Bureau of Reclamation, Denver, Colorado. June 26.

Satterthwaite, F. G. 1946. An approximate distribution of estimates of variance components. Biometrics. 2(6):110-114.

Smith, R. A., R. B. Alexander, and M. G. Wolman. 1987. Water quality trends in the Nation's rivers. Science. 235:1607-1615.

Snedecor, G. W. and W. G. Cochran. 1980. Statistical Methods. The University of Iowa Press, Ames, Iowa.

J. C. Loftis, R. C. Ward, R. D. Phillips, and C. H. Taylor are with Colorado State University, Fort Collins, CO 80523.
***D. H. Landers** is the EPA Project Officer (see below).*
The complete report, entitled "An Evaluation of Trend Detection Techniques for Use in Water Quality Monitoring Programs," (Order No. PB 90-100 058/AS; Cost: $21.95, subject to change) will be available only from:
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
Telephone: 703-487-4650
The EPA Project Officer can be contacted at:
Environmental Research Laboratory
U.S. Environmental Protection Agency
Corvallis, OR 97333

United States
Environmental Protection
Agency

Center for Environmental Research
Information
Cincinnati OH 45268

EPA/600/S3-89/037