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Management Perspective

STATISTICAL ISSUES IN WATER QUALITY MONITORING

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Statistical methods and thinking have an important role to play in water quality monitoring and this is not always well understood. This paper is a summary of an invited roundtable session at the American Statistical Association (ASA) meeting in San Francisco in August 1993 sponsored by the ASA Section on Statistics and the Environment and the Statistical Society of Canada. The co-authors were discussion leaders, with SRE as chair, and all are involved in some aspect of the topic in Canada or USA. The attendees were individuals involved either with US programs, such as EPA regulatory monitoring or large scale status/trend monitoring programs, or university researchers from Canada or USA. The topics covered ranged from basics such as how to get statistics into water quality monitoring to technical aspects such as hypothesis testing versus estimation. Important points to note are the conscensus on 1) the need to have decision makers recognize that statisticians should be involved at all stages of monitoring programs including the very beginnings, 2) the mode is by collaboration and interdisciplinary teams, 3) design is a complex multidisciplinary problem that can benefit from statistical input if quantitative results in line with objectives are to be produced and 4) progress is being made in getting appropriate statistical techniques into compliance monitoring.

STATISTICAL ISSUES IN WATER QUALITY MONITORING

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Introduction

To understand that there is considerable scope for statistical methods and statistical thinking in water quality monitoring, one need only try to define water quality monitoring. Water quality can be defined as the characteristics of a body or source of water. These characteristics are either desirable, which we seek to preserve; or undesirable which we seek to remedy. The characteristics may be linked to a specific use of the water or may be required to maintain the integrity of a natural system. In order to monitor water quality, measurable quantities, often called water quality parameters, which represent the favorable characteristics must be chosen. Water quality monitoring could then be defined as measurement of quantities in time and/or space, where the quantities represent environmental quality, and these quantities are measured in a naturally varying system (sometimes regulated but varying), with the objective of determining status or detecting and estimating changes. The activities of water quality monitoring involve the setting of objectives, the design of the collection program, the collection and analysis of the samples (with all the concomitants), analysis of the data and the drawing of conclusions, and reporting. There are many choices to be made, such as choice of the substrate, of the water quality parameter, and where, when and how to sample. The statistician sees that there are many levels of variability, there are questions of design, detection, and estimation, there is need for adequate representation of uncertainty and for informative summaries; thus many issues where statisticians can make contributions. In keeping with the importance of understanding the system, emphasized by Dr. Deming in the President's Invited Address here in San Francisco, there is also much room for collaboration between statisticians and water scientists.

Of the many issues of statistical importance in water quality monitoring, the primary issue is that of getting more statistical thinking into water quality monitoring and analysis. There are numerous issues associated with the design of studies including problems associated with measurement and response scales in studies involving space and time. A difficult issue is dealing with the interaction between the objectives of monitoring, the characteristics of the system and the statistics used to interpret results. Changes in objectives and refinement of objectives can also create considerable difficulties. Transient and episodic events represent monitoring challenges due to their duration and magnitude. There are additional problems due to the increasing emphasis on measuring ecological aspects of water quality. Finally, the problem of quality assurance and quality control in general if of great importance. Our purpose here is to describe some of our thoughts on these problems and to relate some of the discussion from our roundtable session, held at the meetings in San Francisco.

Getting Statistics Into Water Quality Monitoring

Water quality is not solely a chemical problem. It is also not just a biological problem, a political problem or a problem in human health. The system that is monitored is a dynamic system with many facets and components. Monitoring the system necessitates an interdisciplinary approach. The opinion of the group is that a team approach increases the chance of success. This means that management, researchers and statisticians need to work together. It also means that the statistician in the group needs to become knowledgeable in the subject area and when possible, this means going into laboratories and to the field sites. An example of a good working arrangement has occurred in the U. S. Geological Survey, in which, statisticians have worked together with researchers in assessing trend in water quality. Statisticians have also worked to educate researchers about the need for statistics and the proper use of statistics. It is important that statisticians participate in all phases of the study. There is a need to educate managers about the importance of including statisticians in the early phase of the planning and design of the monitoring program.

Design Issues

Water quality monitoring programs provide a number of challenges. Past experience indicates that there are often difficulties with observations (detection limits, data is rarely normal), difficulties with what is observed (often a large number of variables are measured), difficulties with why measurements are made (objectives of studies frequently change) and difficulties related to when and where measurements are made (convenient location of sampling sites and sampling times). In spite of these problems there are numerous successful monitoring programs. A general feeling was that successful programs tended to be interdisciplinary. The role of the statistician in these groups is important and it is necessary that the statistician be involved early in the planning and development of the program. There is a need to place less emphasis on the view that monitoring is a hypothesis testing exercise and more on the estimation viewpoint. The estimate of the risk is more vital than its existence. Also, the uncertainty associated with these estimates is important. More emphasis needs to be given to estimating variance as well as means in monitoring studies. Recognition needs to be given to the fact that a monitoring program designed for one purpose may not provide data suitable for another objective.

Scaling problems of time and space

One of the fundamental difficulties of water quality monitoring is choosing the appropriate time/space scale to study a process. The environment which we seek to understand is not at a steady-state, nor does it necessarily conform to the expectations of a 'normal' population. There is considerable evidence that the sampling and analysis must take place at the same scales at which phenomena occur. Monthly sampling, while adequate for seasonal phenomena will not provide adequate data for events which take place at a shorter time scale. Spatial scale is also important. Different sized streams may have quite different processes (such as sediment transport) and these need to be considered in a monitoring program which involves different streams.

Educational differences often lead to problems in understanding the importance of scale. Many of the people in the water quality field were trained in biology, and were subjected to classical statistical methods. Thus, for example, time series analysis techniques were considered not as alternate methods, but rather specialized or advanced.

The type of data which is available often restricts our development of understanding of processes in time and space. Understanding of process in one time/space scale may be extrapolated to other scales. This appears to be true for many processes and suggests that environmental processes may be fractal in nature. If the processes are fractal then forecasting to other scales is practical.

Another time scale issue deals with the question of whether or not scales change over time. Some environmental processes may not change with respect to mean level; rather they may become more variable, less variable, or distributed in a different manner.

Environmental monitoring programs are most often concentration based, although other ecological measures are sometimes included. On the temporal scale, most studies consider seasonal and year to year variations. On the spatial scale, most programs consider stations which are tens to hundreds of kilometers apart. It is important to understand that these scales are convenient and expedient, from both operational and political perspectives. They are not chosen because they are environmentally significant.

There are several other features which are often overlooked, but are at least equally important in environmental terms. Events which occur on occasion could be considered on the basis of frequency of occurrence, and of duration of occurrence. Changes in frequency or duration of occurrence may be significant indicators of change, and especially may be indicative of environmental impacts. At the other extreme, long term trends are of concern. Global warming, acidification of surface waters, and desertification being just some examples of this type of long term change.

Other types of trends also exist at other time scales. We typically focus on studies which are short in duration, lasting from several months to a few years. During such studies samples are only collected infrequently. In many cases, such undersampling provides the information needs of the system being studied, without giving any sense of either the short term features or the long term features of the environments being studied. Through this abstraction much of the structure of systems is not appreciated.

Trend patterns of environmental variables frequently have strong covariance patterns. These patterns are not simple and easy to fit using a covariogram, but are often associated with other factors such as land use. It is hard to overemphasize how strongly co-related are patterns of soils, biological characteristics, land use, geology and physiography. Quality at one location may be quite similar to that at a location 50 miles away but very dissimilar to that in a region 5 miles away. Generalized least squares methods have some potential for multilocation trend analysis in these situations.

Many water quality programs may be better served by adaptive designs. Adaptive designs allow for different sampling sites and times and may be combined with more intensive sampling to better address the multiple objectives of management. One of the U. S. Geological Survey's monitoring programs combines sampling at fixed locations but differing scales (nested sites of small, medium and large watersheds with known characteristics) along with broad regional surveys. This allows both in-depth understanding of status and trends in quality at defined locations, as well as putting those locations into a broader context.

Transient and Episodic Events

Many water quality programs, and most 'classical' approaches to water quality monitoring are focused on 'mean water quality' (over time or space). This focus, despite man's experience with floods, spills and other catastrophes. Transients are events which are significant deviations from usual conditions. Usual conditions reflect the cyclic variation we expect to take place with diurnal and seasonal progressions. Transients may have a duration from seconds to days and may occur naturally or as a result of man's activity In general, these events are rare relative to the density of data which are collected. In other words, we often fail to observe such events because we don't make sufficient efforts to look for them. A change in frequency or duration or nature of transients may reflect significant changes in ecosystem integrity.

One broad scale example is the effects of clear cut logging. On an annual basis, the amount of water entering a watershed remains approximately constant. With clear cutting, snow melt takes place over a shorter period of time, transpiration is reduced, and water moves more rapidly through the watershed. The net result is earlier, often larger freshets, coupled with reduced flows during low flow periods. "Mean" conditions remain about the same, however, significant environmental effects often accompany these subtle shifts.

In natural systems, transient events provide some pressures which help ecosystems to remain resilient. Uncoupling these events from the natural systems often leads to ecosystem state changes. Transient events may be significant in a number of ways. Firstly, the nature of a transient event may explain observed ecological impacts. Secondly, transient events may be the significant feature of an environment or environmental problem. Some transients may be characteristic of system functioning and other transients may be symptomatic of human impacts.

Transient events are difficult and costly to study. At present our understanding of such events is quite restricted, and often we end up focusing on the aftermath of an event rather the event itself.

In a more long term sense, environmental managers need to be concerned with transient events from a number of perspectives. The include but are not limited to:

<u>Changes in frequency</u> - how often does a transient occur, and is the process susceptible to changes in recurrence? Examples of increasing frequency of fish kills and spills might be included in this list. We should also be aware of the consequences of reducing the frequency of a class of event. One example of this might be reducing the inundation of wet lands by floods, decreased flood frequency reduces water and nutrient supply and impact on the productivity of wetland.

<u>Changes in duration</u> - how long does a transient last? Examples in changing duration of an event includes the urbanization of watersheds reducing infiltration and reducing the duration of runoff events. Fish may be able to withstand a short period of low dissolved oxygen, or higher temperatures, however the consequences of increased duration of such events can be significant.

<u>Changes in magnitude</u> - how much of a deviation from normal condition is the event? Examples include increased flood magnitudes, increase levels of toxic materials, reductions in essential materials etc. The response of ecosystems to such changes has both immediate and long term effects.

<u>Trends in transients</u> - are multiple changes in the nature of transients taking place in a monotonic fashion? Are such events as floods, spills etc. increasing in a combination of frequency, duration and magnitude? How susceptible to such changes are ecosystems.

Transient events are ecologically significant, they occur in nature and can be significantly altered by human activities. Transients may have consequences which are not a function of duration. In other words, a short duration event can have a large, and or lasting impact on an ecosystem. A forest fire, or a flood is an example of such an event where the consequences are independent of the duration of the event.

Transient events are characteristic of ecosystem functioning. They may be induced by man, natural in origin, or exacerbated by mans actions. One example is the changes in stream chemistry at snow melt, natural in origin, and exacerbated by the loading of acidic materials. How an ecosystem responds to such events may be a characteristic of the ecosystem, changes in the nature of the event might not generate a characteristic response.

Ecological Issues

The recent focus on ecological assessment of health has lead to numerous issues, some which are similar to chemical assessment and some which are quite different. Ecological assessment often involves a large number of species or taxa. Which species to measure is a difficult question. Combining the information from studies of species is also difficult as there are numerous methods for analysis of species data and numerous measures of "ecosystem health." When to sample ecological communities is a complex question. Ecological communities are dynamic, with some species occurring throughout the year, other species having very abundant periods and periods of scarcity and others having various stages of life form. Species interact and are affected by factors other than those related to man made stressors. Separating natural fluctuations from those induced by unnatural conditions can be quite difficult. It may be quite simple to assess toxic effects of pollutants but quite difficult to assess the sublethal effects from sample surveys. More research is needed on ecological effects and better designs are needed to assess status and change.

Compliance Monitoring

Although many of the considerations discussed in other sections of this paper were motivated by monitoring programs designed to assess the current status and trends, in general, they also apply to monitoring to assess compliance with regulations. Other issues which are of concern in compliance monitoring include 1) the enormous number of endpoints (for example, in EPA permits); 2) the use of traditional statistical techniques, which may be well understood but inappropriate; 3) the difficulty of obtaining adequate power when variability is high and reasons for the high variability; 4) the importance of stating null and alternative hypotheses and 5) the effect of litigation on the methods used in assessing compliance. Many of the difficulties can be overcome by more closely matching monitoring program designs to the objectives of the program (that is, decisions that have to be made) and there was a general feeling that agencies were working in this direction. The importance of the estimation of risk, not just its detection, is also being given more recognition.

Quality Assurance and Quality Control

The water quality data we observe is composed of the real value and a variety of sources of error and bias. The collection and interpretation of quality assurance data provides information which allows us to assess the signal to noise ratio amongst our observations. There are few general methods available to assess how we can apply such information.

We must also overcome the present cultural bias towards ownership of data. Much environmental data will be valuable in the distant future if it is properly validated and documented. Incorporating quality assurance into all aspects of environmental monitoring requires new procedures for interpreting quality assurance and observational data

Many agencies collect quality assurance data. Once such data is collected, the investigator has to deal with how to use quality assurance data effectively to determine if the observations collected are real. At present, existing and new techniques which can be properly applied to determine if the observations are 'real' are critical to ensuring the quality of the data we gather.

Statistical Skills Needed by Environmental Scientists

Tomorrow's environmental scientist need a wider exposure to the methods of statistics. This broader exposure must be firmly based on real world problems. Although difficult due to the various backgrounds of students this needs to be done in university statistics classes or in interdisciplinary courses in which statisticians play an important role.

We must teach that each of us has a window on information processing; this is how we see problems and key them to solutions. We need to also deal with issues such as observer bias and problems associated with confounding data - situations where signals of different processes interfere with each other.

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