WATER POLL. RES. J. CANADA
VOLUME 23, No. 4, 1988

DESIGNING SITE-SPECIFIC WATER QUALITY OBJECTIVES AND MONITORING

D. Valiela and P.H. Whitfield
Inland Waters Directorate,
Environment Canada,
502-1001 West Pender Street,
Vancouver, B.C., V6E 2M9

ABSTRACT

The development of site-specific water quality guidelines and objectives requires considering seasonal variability, biologically critical periods, interactions with other variables, and effects of cumulative exposure and lags in functional responses. Designing an effective and efficient monitoring program to determine compliance with site-specific objectives involves allocating the sampling effort according to these factors. We outline a hierarchical approach to determining this allocation process.

INTRODUCTION

Site-specific water quality guidelines provide a scientific basis to develop objectives or standards for water quality management. Socio-economic considerations are also incorporated. The resulting site-specific water quality objectives or standards can be used in concert with other tools, such as land use planning, effluent control, and enforcement of environmental legislation, to enhance management of water quality and aquatic resources.

General water quality guidelines or criteria are helpful starting points for development of site-specific guidelines. General guidelines or criteria are usually based on laboratory toxicology (eg. CCREM 1987; EPA 1980, 1986), and apply to the conditions of the bioassays. In the field, conditions are often different than in the laboratory bioassays. Different species or life stages, different physico-chemical conditions, interactions of the toxicant with other, perhaps fluctuating, variables, cumulative exposure or lag effects, or other conditions restrict the general applicability of the guidelines. Consideration of these factors may result in site-specific guidelines that differ significantly from recommended general guidelines. Site-specific guidelines might include different values at different times of the year and different values for short-term and long-term exposure or to protect specific organisms (e.g. MacDonald et al. 1987).

Monitoring for compliance with site-specific water quality objectives presents a number of challenges. The concentration of the pollutant may exhibit fluctuations that hinder the detection of exceedances of specified levels. Site-specific recommendations may define biologically critical periods when more stringent objectives should be maintained; monitoring effort may need to be concentrated on those periods. The toxicant may interact with other environmental variables. The concentration of such variables may be independent of the toxicant, and itself require monitoring, such as in the case of hardness and metal toxicity. Also, the effects of the toxicant may show time lags or be cumulative with time, and monitoring efforts may need to be directed to detecting these effects.

In this paper we outline a structured approach for site-specific objectives based on examining fluctuations of water quality variables with streamflow, timing of biologically critical periods, toxicant interactions, and lag and cumulative effects of toxicants. This approach facilitates specification of strategies for effective and efficient allocation of monitoring effort to determine compliance with site-specific water quality objectives.

HYDROLOGICAL EFFECTS

Commonly, background fluctuations of water quality variables are related to streamflow in a number of predictable patterns (Whitfield and Whitley 1986). It is important to determine the patterns of that background variability and how the variable to be monitored is related to these patterns. This information can then be used to concentrate sampling effort during periods of the hydrograph when exceedances are most likely to occur. The concentration of a variable may tend to increase with discharge, as in Figure 1a, or decrease with increasing discharge, as in 1b, and tend to show hysteresis (Whitfield and Schreier 1981). Hysteresis effects are evident when two different concentration values occur for each value of discharge, depending on whether the flow is on an increasing or decreasing phase of the hydrograph. Such distributions of concentration values are highly autocorrelated (ie. each value tends to be followed by a similar value). In the case of point source pollutants this relationship may be simply a dilution effect.

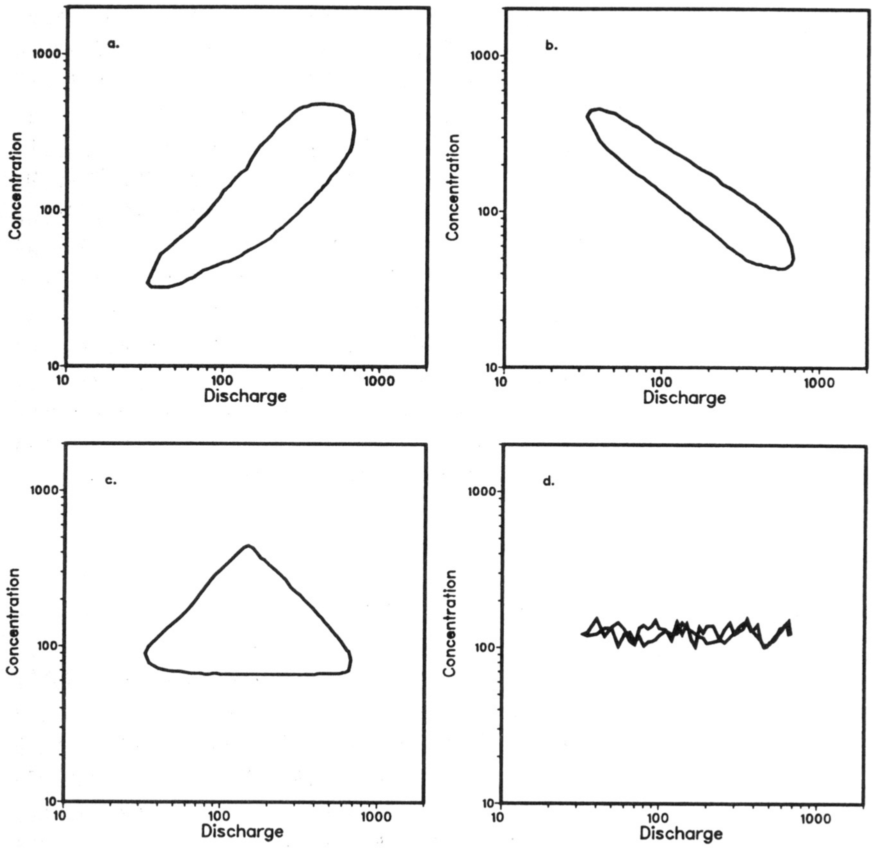

Figure 1. Generalized classes of relationship between water quality variables and discharge in rivers. Examples of data showing these relationships are found in Whitfield and Whitley (1986).

Figure 1c shows the relationship between discharge and a water quality variable, such as chlorophyll, that is independent of flow but is autocorrelated. Variables that are independent of flow and are not autocorrelated can be generally represented as in Figure 1d. The concentrations of some pollutants from anthropogenic sources are often not related to discharge and are similar to Figure 1d. These patterns are generalizations of the most frequently observed water quality - discharge relationships.

Monitoring for compliance with maximum allowable concentrations (i.e., objectives based on acute toxicity; see Valiela and Whitfield 1989) must take account of common patterns of variability, since most monitoring programs are constrained to a relatively small number of samples to be allocated over time. For highly autocorrelated distributions, such as Figures 1a, 1b, and 1c, Valiela and Whitfield (1989) show that "exceedance-driven" sampling, or sampling that becomes more frequent as high values are detected, is more efficient and effective than sampling that is spread out evenly over time. The latter sampling strategy, termed "fixed frequency" sampling, is more advantageous for variables that are not autocorrelated, such as that shown in Figure 1d. Therefore rational allocation of sampling resources requires a good understanding of hydrological relationships so that samples may be taken more frequently when exceedances are expected to occur.

BIOLOGICAL EFFECTS

In many cases, site-specific water quality requirements differ for different life stages or phases of biological processes. For example, the fish species being considered may be most sensitive to a toxicant during the incubation stages and this process may occur during a specific part of each year. This time may be considered a biologically critical period and more stringent water quality objectives may be defined. Allowable concentrations of a toxicant may be lower at this time of the year than at other times, for example in the case of ammonia toxicity to fish larvae (MacDonald et al. 1987) or higher than at other times, as would generally be illustrated by the dissolved oxygen requirements of fish.

Monitoring for compliance with objectives of the type described above can be focussed on these critical times. It is of course necessary to do some monitoring at other times to test for compliance with the objectives that apply the rest of the year.

To focus monitoring effort on these critical periods, it is useful to build upon the previously described patterns of relationships between water quality variables and discharge.

In the case of water quality variables that are positively correlated with flow and autocorrelated, it is convenient to stratify the concentration-discharge diagram into four regions (see Figure 2). This stratification has been done arbitrarily in the present generalized case. If we are monitoring for exceedances over maximum allowable values, most exceedances will occur in an area of high discharge (labeled III in Figure 2a). If these high values coincide with the biologically critical period, then monitoring can be concentrated in that time period and the frequency of sampling can be increased as high values are detected. If the critical period, on the other hand, occurs in another quadrant of this figure, there may be a much lower probability of exceedances that are critical and monitoring effort may be spread out more evenly over time and discharge values. Conversely, concern for minimum values (detecting values below a certain objective level) would justify emphasizing monitoring in quadrant I and keying frequency of sampling to low discharge values.

In the case of variables correlated negatively with flow and showing high autocorrelation, four quadrants can also be conveniently identified as in Figure 2b. Here exceedances over maximum values would be concentrated in quadrant I, and sampling frequency would be keyed to low discharge values. Monitoring for compliance with minimum requirements would concentrate sampling in quadrant III and increase sampling frequency at high discharge values. Both of these strategies apply if the biologically critical periods occur at the same time as the expected exceedances, whether high or low. However, if the biologically critical periods occur at other times in the hydrograph, sampling may be apportioned differently over the hydrographic year and the sampling frequency may not be keyed to high or low values of discharge.

Monitoring for compliance with objectives for variables that are not highly correlated with discharge is somewhat simpler in that the hydrographic year can simply be partitioned into relatively homogeneous portions, as shown in Figures 2c and 2d. When these portions are overlapped with biologically critical periods, quadrants can be chosen for concentration of sampling effort. In the case of 2c, where there is autocorrelation, it may be advantageous, in addition, to use an exceedance-driven monitoring strategy. In the case of 2d, it may be convenient to concentrate on sampling during the biologically critical period, and allocate a portion of the sampling effort evenly among the remaining quadrants. This strategy often applies to monitoring for anthropogenic pollutants, particularly from point sources.

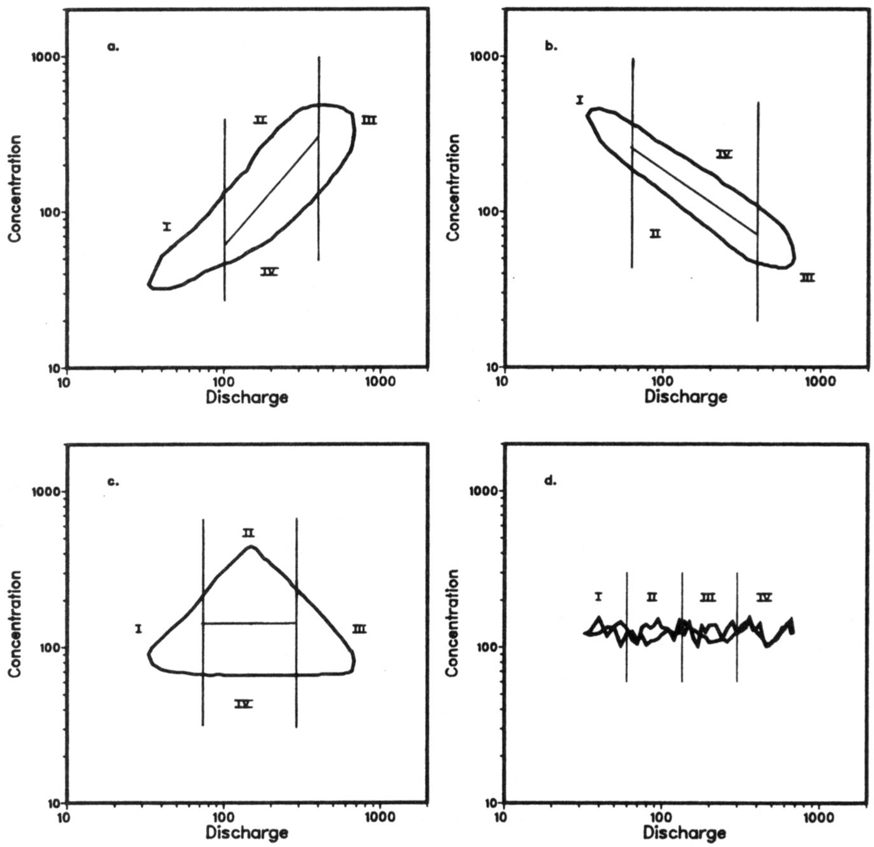

Figure 2. Stratification of the concentration-discharge relationship into four relatively homogeneous quadrants for each class of relationship shown in figure 1.

Allocation of the sampling resource must consider when exceedances are most likely to have a biological effect. This allows sample allocation to ensure that critical periods receive appropriate attention.

INTERACTIONS WITH OTHER VARIABLES

Some water quality guidelines or objectives define values to be met for specific ranges of another variable. One example would be 2.2 mg/l of ammonia for pH 6.5 and 1.4 mg/l for pH 8.0 (CCREM 1987). In designing monitoring strategies for compliance with an ammonia guideline of this type it is necessary to consider the patterns of variability in pH in addition to any biologically critical periods for species and life stages of concern, and to the background or hydrological variability in ammonia concentrations. The overlap of regions of greatest potential concern can be examined by overlaying diagrams of the type shown in Figure 2, and/or graphs of expected values over time. Monitoring effort can then be allocated to those regions of the hydrograph or time periods appearing in such overlays as areas of greatest potential concern.

CUMULATIVE AND LAG EFFECTS

Many water quality variables are involved in ecosystem processes that take time before the effects can be measured or seen. Three examples are phosphorus and eutrophication, PAH's and tissue neoplasms in fish, mercury and Minimata disease. In some cases the delay between cause and effect is due to accumulation of the effects of small impacts over time and thus it is important to establish water quality objectives that specify average values to be met over long periods of time, in addition to the maximum or minimum values not to be violated at any time, as discussed above. Monitoring for compliance with such "chronic" objectives requires representative determination of average values, and is probably most efficiently and effectively done using fixed frequency monitoring (Valiela and Whitfield 1989). Thus a monitoring program to determine compliance with site-specific water quality objectives may include a fixed frequency component throughout the year and a more intensive period or periods of special monitoring, whether fixed frequency at shorter intervals or exceedance-driven, to detect violations of acute requirements.

Some delayed effects of changes in water quality variables may not be simply an accumulation of small effects over time but may be due to a lag or delay inherent in the underlying processes that connect the cause to the effect. An example might be the accumulation of phosphorus in the hypolimnion of a lake and its utilization by phytoplankton only after spring overturn. In these cases, unless the dynamics of the system are understood, it is tempting to monitor existing conditions and, seeing no adverse effects, set water quality objectives equal to an apparent "background." Once the lag period is over it will become apparent that the objectives were not stringent enough, and that the dynamics of the system must be understood to establish useful site-specific objectives and compliance monitoring. In some cases, it is possible to use lag analysis on monitoring data on the variable and the effect (e.g. concentrations of phosphorus and chlorophyll a) to identify the specific variable (concentration of phosphorus at spring overturn) for which objectives should be set and on which monitoring should focus.

CONCLUSIONS

The development of site-specific water quality guidelines requires knowledge of how the variable of interest is related to the hydrograph, whether there are any significant biologically critical periods, the nature of important interactions with other environmental variables, and whether there are significant cumulative or lag effects of the variable under consideration. Site-specific guidelines and monitoring must therefore define the requirements imposed by each of these considerations and their timing. These requirements could be visualized as a flow chart (D. D. MacDonald personal communication), and eventually as a potential application of expert system approaches.

Monitoring for compliance with site-specific objectives must be defined in the objectives and must reflect environmental complexities. Since monitoring resources are always limited, it is important to direct most of the sampling effort to periods of greatest potential concern. Identification of these periods involves joint consideration of a number of patterns in time and is facilitated by a structured hierarchical approach.

REFERENCES CITED

Canadian Council of Resource and Environment Ministers (CCREM). 1987. Canadian Water Quality Guidelines. Toronto, Ontario.

MacDonald, D.D., L. E. Fidler, and D. Valiela. 1987. Site specific water quality criteria for fish and aquatic life in the Canadian portion of the Flathead River basin. Nitrate, nitrite and ammonia. Inland Waters and Lands. Environment Canada. Pacific and Yukon Region Report 127pp.

United States Environmental Protection Agency (EPA). 1980. Ambient water quality criteria for polychlorinated biphenyls. Office of Water Regulations and Standards, Criteria and Standards Division. U.S.E.P.A., Washington, D.C., EPA-440/5-80-068.

United States Environmental Protection Agency (EPA). 1986. Bacteriological ambient water quality criteria for marine and fresh recreational waters. Office of Water Regulations and Standards, Criteria and Standards Division. U.S.E.P.A., Washington, D.C., EPA-440/5-84-002.

Valiela, D., and P.H. Whitfield. 1989. Monitoring strategies to determine compliance with water quality objectives. In press, Water Resources Bulletin.

Whitfield, P.H., and H. Schreier. 1981. Hysteresis in relationships between discharge and water chemistry in the Fraser River basin, British Columbia. Limnology and Oceanography 26:1179-1182.

Whitfield, P.H., and W.G. Whitley. 1986. Water quality-discharge relationships in the Yukon River basin, Canada. In: D.L. Kane (Ed.) Proceedings of the Cold Regions Hydrology Symposium pp. 149-156. American Water Resources Association.