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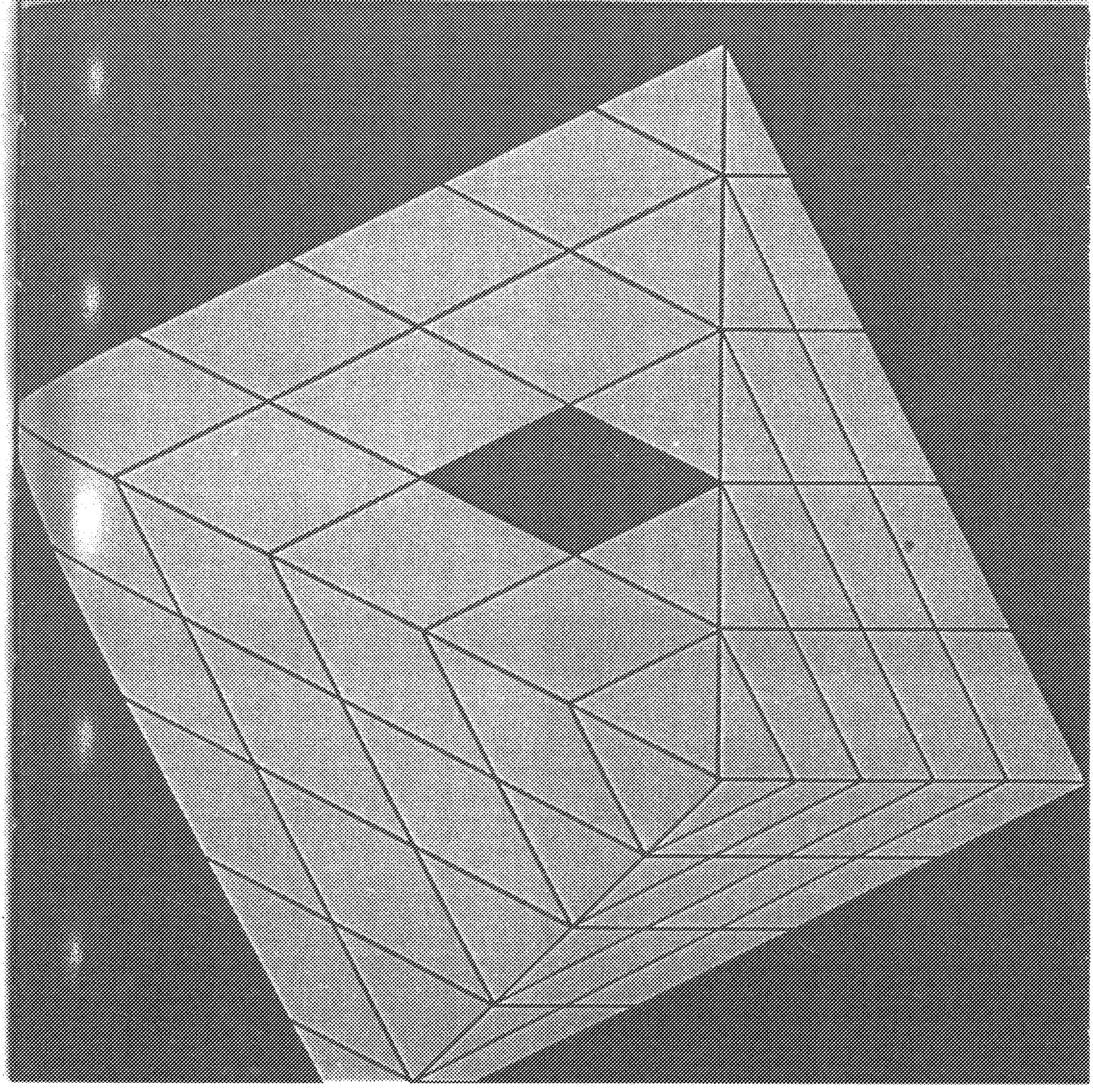

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A Design for Aquatic Monitoring Programs†

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An objective of ecological aquatic monitoring at nuclear power plants has been the detection of impacts on the important fauna and flora in the vicinity of the plant site. A control–treatment pairing (CTP) design for monitoring programs is presented for impact assessment in benthic and plankton communities. A scheme for the establishment of monitoring programs using CTP designs is discussed which accounts for the influence of plant site characteristics, the quantitative objectives of the monitoring study, the expected magnitude of experimental error and the limitations of time and effort. A graphical technique is presented which can be used to incorporate these often competing constraints into the design of aquatic monitoring studies. Estimates of the experimental error computed from *a posteriori* applications of CTP designs to benthic and plankton communities at six nuclear power plants are presented.

Keywords: impact assessment, ecological monitoring, experimental design, statistics, plankton, benthos, nuclear power plants.

1. Introduction

Ecological assessment is a process of estimating the biological costs of a potential impact on an ecosystem. The Nuclear Regulatory Commission (NRC) in the past has required an ecological impact assessment for nuclear power plants before construction and operating licenses were issued; their purpose was to determine if development of a plant was consistent with national environment goals as specified in the National Environmental Policy Act (NEPA) of 1969. Monitoring programs were established to identify the important flora and fauna in the region of the plant site and provide the basis for assessment of changes in biota resulting from plant operation or natural variability. The implied objective of ecological monitoring at nuclear power plants (NPP) has been either to detect an impact if it occurred or to estimate the magnitude of an impact. However, Gore *et al.* (1977), in reviewing environmental monitoring programs at NPP for the

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NRC, concluded that most monitoring programs were not designed for statistical analysis or detecting changes in biota.

The important criterion when establishing a monitoring program is to find an experimental design capable of identifying changes which are directly attributable to the effects of the power plant. Since population abundance of organisms varies both temporally and spatially, a monitoring design should be able to differentiate the effects of this natural variability from those population changes which result from impact. Eberhardt (1976*a,b*) and Thomas and Eberhardt (1976) suggested that the ratio of population abundance between non-impact/control and impact/treatment sites be used to quantify impact. They defined an impact as a change in this ratio of abundance between pre-operational and operational phases of an NPP. McKenzie *et al.* (1977) used *a posteriori* application of this control–treatment pairing (CTP) design to evaluate plankton and benthic monitoring programs at three NPP.

This paper presents recommendations for the establishment of plankton and benthic monitoring programs at NPP using the CTP design. The nature and extent of a monitoring program depends on a number of constraints:

(1) the site specific environmental characteristics at the nuclear power plant,

(2) the quantitative objectives of the monitoring program,

(3) the experimental error,

(4) the limitations of time and effort for concluding the monitoring program.

It is the objective of this article to discuss how these constraints may affect the implementation of CTP monitoring program designs.

2. The control–treatment pairing design

The purpose of the CTP monitoring program design is to quantify changes in organism abundance that might occur as a result of NPP operations. Thus, the CTP design pairs potentially impacted/treatment stations with non-impacted/control stations to assess impact. The treatment stations are located within the zone of potential power plant influence while the control sites are positioned outside the zone. As in classical experimental design, a control is used to measure the effects of the experimental (ambient) conditions while the treatments measure the environmental conditions plus the effects of an added stimulus, the impact. A critical requirement of CTP designs is the selection of stations for the control–treatment pairs where organism abundance responds similarly to changes in environmental parameters.

Unlike classical experimental designs, however, such treatment and control stations cannot be randomly assigned to test plots. In the ecological monitoring of a power plant impact, there is only one treatment area and there may or may not be more than one control area. For the CTP design, several sampling stations are established within the treatment and control areas, a procedure Eberhardt (1976*a,b*) calls a "pseudoexperiment" or "pseudodesign".

In the CTP design, the control–treatment pairs are established during the pre-operational phase of the NPP monitoring and those station pairs are sampled into the operational period. Sampling during the pre-operational period serves two functions. First, pre-operational sampling can be used to evaluate the success of the pairing scheme prior to the operational status of the NPP. More importantly, the pre-operational sampling establishes the relationship of organism abundance between the control and treatment stations, e.g. proportional abundance, which will be compared later with that observed during the operational period. With this ecological assessment scheme, impact is then defined as a statistically significant change in the proportional abundance of organisms at control and treatment stations between pre-operational and operational periods. By the use of estimates of the proportional abundance between control and treatment areas, CTP designs help to eliminate the problems of confounding impact effects with temporal and spatial changes in abundance. Designs for impact studies recommended by Green (1979) and methods for their analysis recommended by Elliot (1977) and Green (1979), however, do little in resolving these problems.

A critical assumption in the CTP design is that organism abundances at control and treatment stations "track" each other, i.e. maintain a constant proportionality. This tracking ensures that organism abundance at the control and treatment stations responds similarly to changes in environmental conditions. Unless this assumption is valid, there is no way to determine if changes in abundance at the treatment stations during the operational period are the result of temporal variability or the impact of the NPP.

The proportional abundance of organisms between the control and treatment stations is used in the analysis of monitoring data from CTP designs. There are two assumptions associated with the analysis of proportional abundance. First, a constant proportional abundance can be used to remove annual and seasonal changes in abundance when stations are well paired. Removal of the annual variation allows repeated observations of a treatment combination between years to be designated as replication. Each year of the pre-operational or operational phase of the monitoring program is considered as one replicate in the analysis of CTP designs. Second, use of proportional abundance reduces the serial correlation that can exist among successive observations of abundance at sampling stations (McKenzie *et al.*, 1977). Serial correlation within data has been found to hamper analysis of variance procedures (Scheffé, 1959).

For the assumptions in the analysis of the CTP data to be valid, the relationship between organism abundance at the control and treatment stations must be known or estimated so that annual changes can be removed. Analytically, the observations on abundance can be handled in three common manners: as untransformed differences in count and biomass data, as differences in the square roots of the data, and as logarithmic transformations of the ratio of abundance. The proper transformation of the data should depend on the nature of the response being studied and the distributional characteristics of the observed random variables (abundance). McKenzie *et al.* (1977) reviewed the assumptions and merits of these transformations used on monitoring data. In this report, only the logarithmic transformations of the data will be considered. Use of the logarithmic transformation of the ratio of abundance assumes that a constant proportional relationship exists between organism densities at the control and treatment stations. Further, use of a logarithmic transformation assumes that the factors affecting abundance have a multiplicative effect which can be linearized by the transformation.

When good control–treatment pairing is achieved, the variance of the difference in densities between the control and treatment stations should be reduced. The variance of the difference between two random variables, X_1 and X_2, can be expressed as

$$\operatorname{var}(X_1-X_2)=\operatorname{var}(X_1)+\operatorname{var}(X_2)-2\operatorname{cov}(X_1, X_2).$$

With favorable pairing, the covariance between density values at control and treatment stations should be positive, thus decreasing the observed variance and resulting in increased power of the tests of hypothesis.

3. Recommendations

Each of the four constraints mentioned as important in implementing CTP designs will now be discussed. A graphical technique will be presented later which can be used to incorporate these often competing constraints into the design of an aquatic monitoring study.

3.1. SITE SPECIFIC CHARACTERISTIC OF AN NPP

Station pairs selected for the monitoring design should possess combinations of environmental factors which are considered important in affecting organism abundance. The factors to include in the design will in large part depend upon the site specific characteristics of the nuclear power plant and the organisms studied. The factors influencing density should be arranged in an array of conditions typically called a "factorial treatment design". For each of the environmental factors, two or more levels of treatment reflecting differences in potential influence on organism densities need to be identified. The factorial treatment design is then constructed by forming all possible combinations among the different factors at their various levels.

Since the objective of a monitoring program is to determine whether the operation of an NPP has affected organism abundance, station pairs are sampled during both pre-operational and operational phases. The first factor in the treatment design is, therefore, the status of the NPP. Additional factors which may affect organism abundance must also be included in the design.

In plankton communities, the depth at which a water sample is collected may have a direct influence on organism abundance. Therefore, the depth at which a plankton sample is collected is a potential factor in the design and a distinction is made between depth strata. The abundance and species composition of plankton is seasonal in nature, so time of the sampling should usually be included as a factor in the design. If sampling is conducted monthly, 12 levels of treatment for the time of sampling can be considered. Six levels can be considered if sampling is at two-month intervals, and four levels if seasonal or quarterly samples are collected. Other factors, such as the distance from the shore line or the depth contour at which the sampling station is located and the location of the station pairs relative to the NPP, may also be important.

In a study of benthic communities, the depth in the water column at which a sample is collected is not considered a factor since all organisms are located on the bottom. In benthic studies, however, the type of substrate on which the sampling stations are located and whether they are located in the intertidal or subtidal zone should be considered. The various substrate types and tidal zones may be considered either as factors in the analysis or separated into individual monitoring programs.

An example will help illustrate the nature of the factorial treatment design. Consider the plankton study at Zion Nuclear Power Plant (Figure 1, also see McKenzie *et al.*, 1977). The factors (A–E) and their levels of treatment (a–e) can be summarized.

(A) Status, two levels—pre-operational and operational, $a=2$.

(B) Depth at which sample was collected, one level—surface only, $b=1$.

(C) Time of sampling, 12 levels—monthly samples were collected, $c=12$.

(D) Location of station pairs at depth contours, three levels—located at 10 feet (3·0 m), 30 feet (9·1 m), and 60 feet (18·3 m) contours, $d=3$.

(E) Relative position of the station pairs, two levels—north and south of the NPP, $e=2$.

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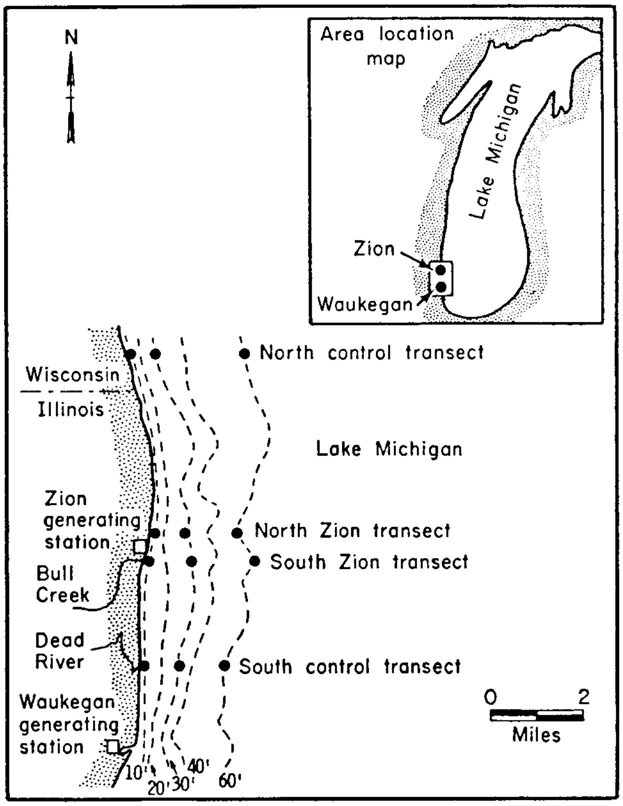

Figure 1. Location of control–treatment stations for plankton sampling near Zion NPP.

For the Zion example, the different factors at their various levels define 144 ($=a\times b\times c\times d\times e=2\times 1\times 12\times 3\times 2$) distinct treatment combinations in the factorial treatment design.

For the above example, a multiplicative model describing the ratio of abundance for control (C) and treatment (T) pairs can be written as:

$$Y_{acdek}=\mu\cdot A_a\cdot C_c\cdot D_d\cdot E_e\cdot(AC)_{ac}\cdot(AD)_{ad}\cdot(AE)_{ae}\cdot(CD)_{cd}\cdot(DE)_{de}\cdot\epsilon_{acdek} \tag{1}$$

where

$Y_{acdek}=(C_{acdek}/T_{acdek})$=value of the kth replicate ($k=1,\ldots,n$) for the ratio of the control–treatment pair described by factors A, C, D, E at appropriate levels.

μ=overall mean effect

A_a=main effect of factor A at level $a=1,2$

$(AC)_{ac}$=two-factor interaction effect, $a=1,2$ and $c=1,\ldots,12$

ϵ_{acdek}=multiplicative error term, $k=1,\ldots,n$.

Note for factor B, $b=1$ so the factor is excluded from the model equation. This model depicts a completely randomized experimental design and assumes that second order interactions and above are negligible.

The logarithmic transformation of the model equation (1) results in the linearized model:

$$\begin{aligned}\log Y_{acdek}=&\log\mu+\log A_a+\log C_c+\log D_d+\log E_e+\log(AC)_{ac}\\&+\log(AD)_{ad}+\log(AE)_{ae}+\log(CD)_{cd}+\log(CE)_{ce}\\&+\log(DE)_{de}+\log\epsilon_{acdek}\end{aligned} \tag{2}$$

where

$$\log Y_{acdek} = \log C_{acdek} - \log T_{acdek}$$

$$\log \mu = \text{overall mean of the transformed data}$$

$$\log \epsilon_{acdek} = \text{additive error term.}$$

Employing the logarithmic transformation equation (2) assumes the error terms in equation (1) were log-normally distributed so that after transformation they are normally distributed with mean zero and constant variance.

When suitable station pairs can be found and established, a number of design properties still need to be considered. The properties of orthogonality and balance must be addressed in the design of a monitoring program. An orthogonal design requires that a level of a factor appears an equal number of times with all levels of another factor. For example, within the factor status, each treatment combination in the pre-operational period must also be present in the operational period for the design to be orthogonal. In order for a design to be balanced, each unique treatment combination must be replicated an equal number of times. For the CTP design this requires, for example, equal duration and sampling intensity for the pre-operational and operational phases of the monitoring program.

Orthogonal and balanced monitoring designs greatly simplify and improve the analysis of the data collected. Data sets that are not balanced or not orthogonal often arise when sampling periods or stations are missed during data collection. Effort should be taken to ensure as close a balanced design as possible. For the large factorial treatment designs characteristic of monitoring programs, extreme lack of balance and/or orthogonality can produce results that are uninterpretable.

3.2. QUANTITATIVE OBJECTIVES OF THE MONITORING PROGRAM

The objectives of a monitoring program must be established explicitly before the field design for the monitoring program can be properly determined. The monitoring objectives usually consist of two components. A delineation of the response variables to be monitored defines the ecological objectives of the program. The choice to monitor total community biomass or just economically important, endangered or indicator species has a profound effect on the ecological significance of a monitoring program. Specifying the magnitude of a change which is ecologically significant or important to detect defines the quantitative objectives of the monitoring program. The quantitative objectives must include:

(1) the size of change in abundance, Δ, considered important to detect,

(2) the probability, α, of declaring a significant impact when none has occurred,

(3) the probability, $(1-\beta)$, of detecting a change in abundance of size Δ or greater when such a change has occurred.

The selected values of Δ, α and β are subjective decisions and, because their choice influences the sensitivity and detectability of a monitoring program, they must be established prior to the monitoring.

A definition of Δ is the difference in the log of the ratios of abundance at control (C) and treatment (T) sites between pre-operational (P) and operational (O) periods, such that

$$\Delta = \log \frac{T_O}{C_O} - \log \frac{T_P}{C_P}.$$

Further, let ρ=the proportionality constant for abundance between years, and let γ= the fractional change in density at the treatment site resulting from impact of the NPP.

Then, $$C_O=\rho C_P \text{ and } T_O=(1+\gamma)\,\rho T_P$$

and $$\Delta=\log\frac{(1+\gamma)\rho T_P}{\rho C_P}-\log\frac{T_P}{C_P}$$

$$\Delta=\log(1+\gamma).$$

For example, if a 30% decrease in density at the treatment site is to be detectable, then $\Delta=\log(1-0{\cdot}3)=-0{\cdot}1549$. The size of Δ for a 50% increase in density would be $\Delta=\log(1+0{\cdot}5)=0{\cdot}1761$. This derivation of Δ stresses that a constant proportional relationship must exist between densities at control and treatment stations and indicates the importance of proper station pairing to eliminate annual effects. The definition of Δ also indicates that the CTP designs are more sensitive to impacts resulting in decreased abundance than impacts producing an increase in abundance at treatment stations since

$$|\log(1-\gamma)|>|\log(1+\gamma)| \text{ for } 0<\gamma<1.$$

Because most impacts of major concern result in reduced productivity, the greater sensitivity of CTP designs to depletions in organism abundance is an advantage.

As the absolute value for the choice of either γ or Δ decreases, the magnitude of the monitoring program must be increased to maintain a given α and β. The size of a monitoring program can be increased either by extending the length of the pre-operational and operational periods or by increasing the number of factorial treatment combinations. In this paper, we will consider only monitoring programs with two or three year pre-operational and operational periods. The size of the monitoring program under this constraint will be enlarged by increasing the number of sampling periods or stations.

The values of α and β chosen will also influence the size of the monitoring program. The higher the chosen probability $(1-\beta)$ of detecting a change in density of size Δ, the larger the monitoring program must be for a given Δ and α. Also, the smaller the chance (α) one wishes of declaring a significant impact of size Δ, when in actuality it has not occurred, the larger the monitoring program must be for a given Δ and β.

Hence, it is evident that the size of the monitoring program is closely related to the quantitative objectives of the program as expressed in terms of the values of Δ, α and β. McKenzie *et al.* (1977) suggest using the values of $\alpha=0{\cdot}10$ and $\beta=0{\cdot}20$ for the analysis of aquatic monitoring data collected for power plant impact assessments, and, in this report, all design considerations will incorporate these values. This choice of values for α and β should not be construed, however, to imply these are the only values which are correct.

In this paper, the value of Δ will be allowed to "float" so that monitoring designs can be evaluated on the basis of how sensitive they are to changes in organism abundance. By this procedure, values of Δ can be selected which may have a biological significance for the specific populations or communities being studied.

3.3. EXPERIMENTAL ERROR

The natural variability in organism abundance between sampling pairs and sampling periods will have a direct effect on the design of a monitoring program. The greater the temporal and spatial heterogeneity in organism abundance at the monitoring site, the greater the sampling effort must be. For specified values of Δ, α and β, as variability increases, so must the sampling effort.

The variability in organism abundance is expressed as the mean square for error (MSE) or experimental error associated with the monitoring program. The value of MSE is an unbiased estimate of σ^2, the variance between replicates of a control-treatment pair. Estimates of σ^2 are required in designing a monitoring program to compute the number of treatment combinations and the duration of a proposed study needed to fulfil the quantitative objectives.

Table 1 provides a summary of estimates of the experimental error (MSE) derived by *a posteriori* application of CTP designs to plankton and benthic data from six NPP (McKenzie *et al.*, 1977, 1979). Estimates of the experimental error are provided for count data on zooplankton, phytoplankton and benthic organisms and chlorophyll *a* measurements of phytoplankton productivity. An expanded list of values of MSE from the analysis of count data for algae, diatoms and selected invertebrates, pheopigment concentrations and fauna and flora biomass may be found in McKenzie *et al.* (1977, 1979). The relative stability among the estimates of experimental error for plankton communities (Table 1) suggests the reported values of MSE could be used as a satisfactory basis to estimate the size of future monitoring programs. For benthic communities where a much greater variability among values of MSE exists, the values of MSE could be used to design future programs but with less certainty, i.e. a greater risk of either underestimating or overestimating the size of the proposed monitoring program.

TABLE 1. Comparison of values of MSE from benthic and plankton studies using a $\log_{10}$ transformation of the data and computed by analysis of variance employing CTP designs

Data set	Location	MSE	*d.f.*	Habitat type
Total zooplankton counts (numbers/m^3)	†Zion NPP	0·048	283	Lake
	San Onofre NPP	0·073	28	Marine
	San Onofre NPP	0·089	29	Marine
Total phytoplankton counts (numbers/m*l*)	†Haddem Neck NPP	0·042	44	River
	†Prairie Island NPP	0·036	8	River
	†Zion NPP	0·075	286	Lake
	Calvert Cliffs NPP	0·026	70	Chesapeake Bay
Total benthic counts (numbers/m^2)	†Haddem Neck NPP	0·192	166	River
	†Zion NPP	0·112	173	Lake
	Pilgrim NPP			Marine
	intertidal, rocky	0·311	20	Marine
	subtidal, rocky	0·823	30	Marine
	subtidal, sandy	0·036	19	Marine
Chlorophyll *a* (mg/m^3)	San Onofre NPP	0·093	29	Marine
	San Onofre NPP	0·086	29	Marine
	Calvert Cliffs NPP	0·051	22	Chesapeake Bay

† McKenzie *et al.*, 1977.

How closely the initial estimate of MSE is to the actual value observed during the monitoring program will determine if the quantitative objectives of the program are achieved. If the initial estimate of MSE is below the value observed, the number of treatment combinations or the duration of the study will be underestimated. Underestimation of the size of the monitoring program will result in reduced sensitivity and power of detecting changes in abundance that are the result of NPP impact. When the initial estimate for the value of MSE is larger than the value observed, the size of the study will be overestimated. Greater detectability and power will result from the overestimation of MSE, but at an additional cost for conducting the monitoring program.

3.4. LIMITATIONS ON TIME AND EFFORT

Final considerations in the design of any monitoring program must be the limitations of time, effort and cost. After the quantitative objectives of the study have been stated and the site specific requirements of the study including experimental error (MSE) have been considered, the practical problems of implementation remain.

As will be seen, the objectives of the study and the value of MSE chosen will primarily determine the number of treatment combinations and the duration of the monitoring program needed. Within the limitations of the chosen values of α, β, Δ and MSE, several field study designs may be acceptable. The field design is defined by the factorial treatment design used in the monitoring program.

Certain flexibility usually exists in the possible factors and levels of treatment to include in a monitoring design. This flexibility can be used to design monitoring programs which best fit the limitations of time and effort. If limitations exist on the number of sampling stations that can be established and maintained, the number of sampling periods per year and the duration of the study can often be adjusted to accommodate such restrictions. When the duration of a monitoring study is a limiting factor, the number of sampling stations or the intensity of the sampling may be increased to adjust for the shorter time periods.

The adjustment of factors and levels of treatment to accommodate the limitations in manpower and time must be tempered by several considerations. Establishment of additional station pairs should occur only in those areas where the treatment sites are within the zone of potential impact by the NPP. Extending station pairs along depth contours outside the influence of the power plant will likely introduce significance of the "NPP operational status by location interactions" in the analysis of the monitoring data. The presence of significant interaction terms among the factors can greatly complicate the interpretation of results.

Problems can also be encountered if numerous station pairs are placed too close to each other for the sole purpose of increasing sample size. The station pairs in this case serve only as additional subsamples of an area, not replicates, and may inappropriately decrease the observed experimental error. An experimental error based on subsampling, rather than the within treatment variance which is normally used in analysis of variance procedures, may produce erroneous hypotheses testing results.

Care should also be taken when increasing the frequency of sampling. Too frequent a sampling scheme may produce observations with high serial correlation and should be avoided if analysis of variance procedures are to be employed. At most, monthly and bimonthly samples of plankton and benthic organisms, respectively, are recommended if high serial correlation is to be avoided (McKenzie *et al.*, 1977).

4. Design of monitoring programs

The steps used to design a monitoring program will be considered more fully now that a discussion of the various constraints is complete. Consideration will be given to monitoring programs which can be defined by any subset of the following factors and treatment levels:

(*A*) plant operating status: two levels,
(*B*) depth at which sample was collected: one or two levels,
(*C*) times of sampling: four, six or 12 levels,
(*D*) depth contours: one, two, three, four or five levels,
(*E*) position of station pairs relative to the NPP: one or two levels.

These factors and their levels of treatment are considered fixed effects in the analysis of variance. A majority of the monitoring programs using CTP designs to study benthic or plankton communities can usually be defined by the parameters given above. All monitoring programs will be assumed to use the values $\alpha=0{\cdot}10$ and $\beta=0{\cdot}20$.

Again let a, b, c, d and e define the number of treatment levels for factors A through E, respectively. For example, plant operating status will always have pre-operational and operational levels in a monitoring design, so $a=2$. With this notation, the number of station pairs for a proposed design will equal $d\times e$ (=number of station pairs, control +treatment, located at d contours and e locations about NPP) and so the number of control and treatment stations needed for a monitoring program will be $2de$. Similarly, the number of benthic or plankton samples collected during any one sampling period will be equal to $2bde$, where b defines the number of depths at which samples are collected per station.

Using the power function of the F distribution (Tiku, 1972), the size of change Δ that is detectable by a proposed monitoring program at $\alpha=0{\cdot}10$ and $\beta=0{\cdot}20$ can be determined. This level of detectability depends not only on the values of α, β and MSE, but also on the degrees of freedom associated with the hypothesis test. The hypothesis of interest is whether the main effect for the factor status equals zero. The null hypothesis to be tested states no difference exists in the proportional abundance of organisms at control and treatment stations between pre-operational and operational phases of the NPP. The degrees of freedom associated with the F-test for status main effects are:

$$d.f._1=1$$

$$d.f._2=nabcde-\sum_{v=a}^{e}(v-1)-\tfrac{1}{2}\left[\sum_{v=a}^{e}\sum_{\substack{w=a\\ v\neq w}}^{e}(v-1)(w-1)\right]-1$$

where

n=number of replications, either two or three years.

The degrees of freedom for the denominator of the F-test ($d.f._2$) depends on the design of the monitoring program and the method of analysis as represented by the model equation (2). As stated earlier, the monitoring programs are conceptualized in this paper as completely randomized designs and where second-order or higher interactions are considered small.

Figures 2a–d present graphs of the power function of the F-test for the main effect for status. Figures 2a and b indicate the size of change in plankton abundance detectable for various monitoring designs with two and three year pre-operational and operational phases, respectively. Similarly, Figures 2c and d indicate the change in benthic organism abundance detectable in studies with two and three year pre-operational and operational phases, respectively. The values of MSE used in Figures 2a–e were the minimum, maximum, and average values observed in the analysis of plankton and benthic monitoring studies at NPP reported earlier (Table 1).

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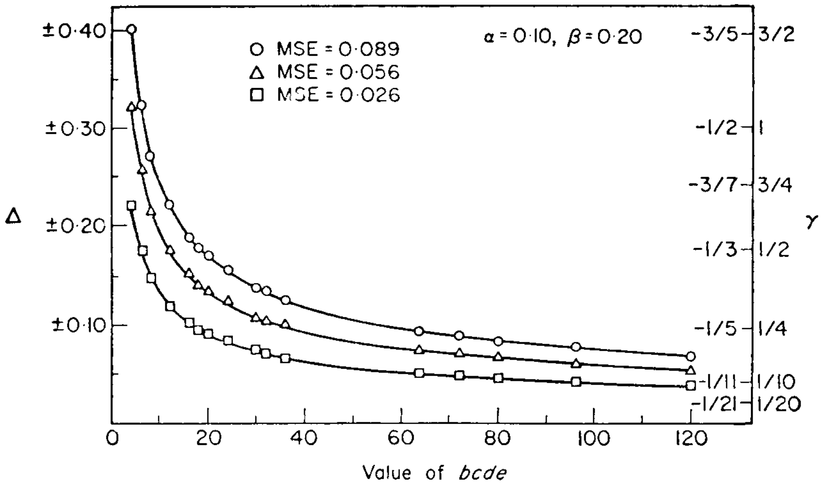

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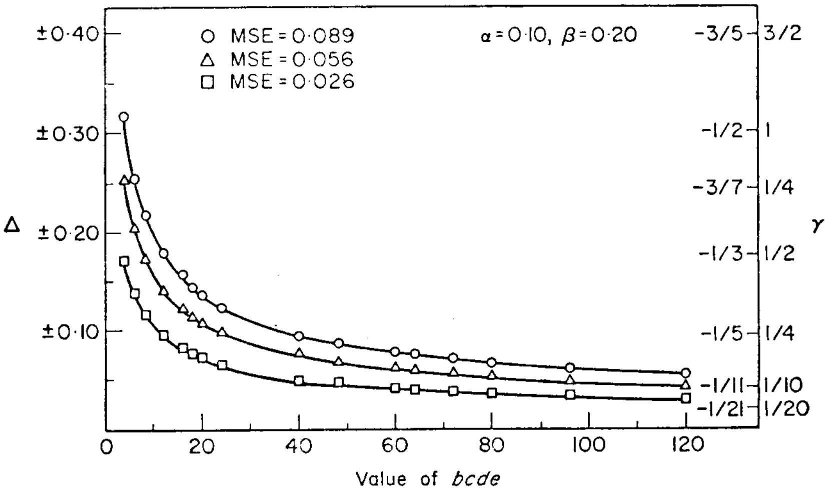

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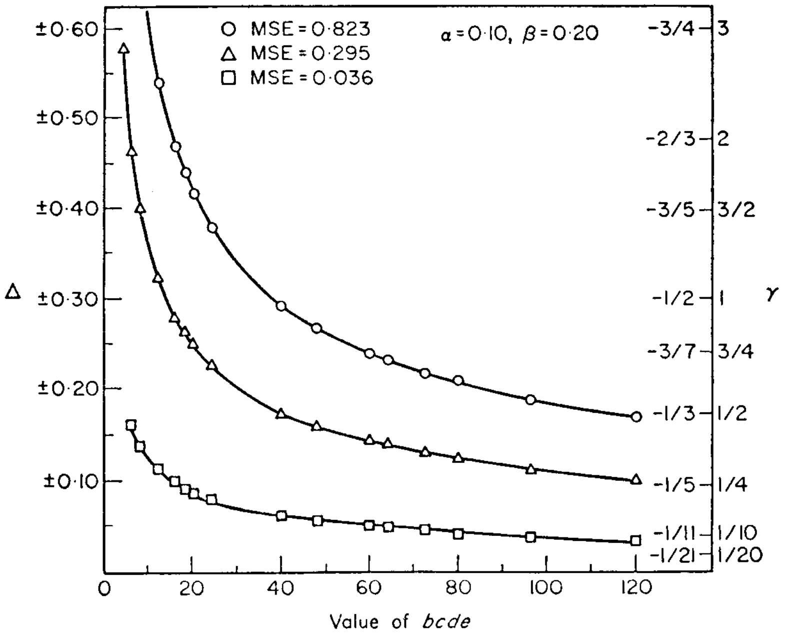

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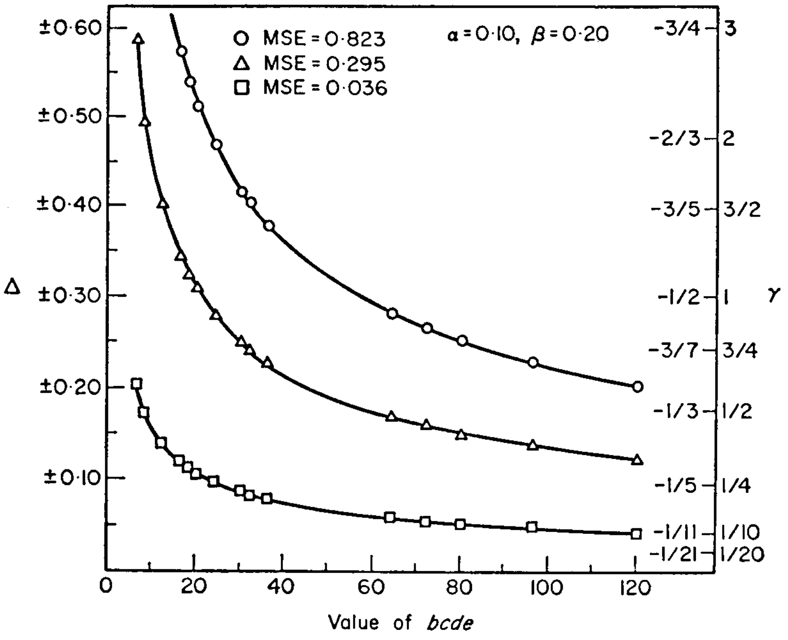

(2d)

Figure 2. Power curves for the *F*-test ($\alpha=0{\cdot}10$, $\beta=0{\cdot}20$) of no NPP-status main effects using CTP designs. The value of *bcde* is the total number of control–treatment samples collected during one year of monitoring. Values of MSE are the minimum, maximum and average values observed in analysis of data for plankton and benthic communities (Table 1). (a) Plankton studies with two year pre-operational and operational phases. (b) Plankton studies with three year pre-operational and operational phases. (c) Benthic studies with two year pre-operational and operational phases. (d) Benthic studies with three year pre-operational and operational phases.

In Figures 2a–d, the various monitoring designs are represented by values of *bcde*, the number of control–treatment samples collected during one year of a monitoring program. However, different values of *b*, *c*, *d* and *e* can result in the same value of *bcde*; for example, $bcde=2\times4\times3\times2=1\times6\times4\times2=48$. Using this flexibility, Figures 2a–e can be used as graphical aids in constructing aquatic monitoring designs which incorporate the constraints of the plant site characteristics, quantitative objectives, experimental error and limitations of time and effort. The degrees of freedom (*d.f.*) for the *F*-test of status main effects for the two examples above differ. The first has 1 and 159 *d.f.*, while the second has 1 and 149 *d.f.* for a four year monitoring program. For a given value of MSE, the detectability (Δ) changes with a change in $d.f._2$ but not enough to be distinguished on the figures.

4.1. EXAMPLE: ZION NPP

For the example of the plankton study at Zion NPP, the value of $bcde=1\times12\times3\times2=72$. If the value of MSE from the analysis of plankton data at Zion NPP was 0·089, the monitoring design would be capable of detecting a change as small as a 22·3% increase in abundance or a 18·2% decrease in abundance between pre-operational and operational phases if monitored two years each (see Figure 2a). In a three year pre-operational and three year operational study, a change as small as a 17·5% increase or 14·9% decrease in abundance could be detected (see Figure 2b).

A relevant question to ask would be: "What size monitoring program is needed to detect a 33% reduction in plankton (or 50% increase in abundance)?" Using the maximum observed value of MSE=0·089 (Table 1), Figures 2a–b indicate values of

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bcde of 19 and 12 are required for two and three years per phase studies, respectively. One design for a monitoring program giving a value of $bcde \geq 19$ would be $1 \times 6 \times 2 \times 2 = 24$. This design would require bimonthly sampling of two station pairs at two locations near the NPP for a period of two years pre-operational and two years operational.

Numerous other monitoring designs would produce values of $bcde \geq 19$. The choice of the proper design should depend on the site specific characteristics of the NPP and the limitations of time and effort. More levels of treatment should be given to those factors which may more likely be associated with an effect of an impact due to the NPP. For example, if impact is suspected to occur seasonally, frequent sampling would be desired to ensure such a response would be detected. Thus, the flexibility in potential field designs permits the design of monitoring programs which best fit the site-specific characteristics of the NPP.

4.2. EXAMPLE: A BENTHIC MONITORING DESIGN

A similar question can be addressed of benthic monitoring: "What size monitoring program is necessary to detect a 33% reduction in species abundance?" To answer the question, the value of MSE to expect would have to be known. For this scenario, assume the value of MSE to expect is unknown and must be guessed. Further, it is decided that tidal and subtidal zones should be monitored separately since species composition is different and any quantitative comparisons between zones would be difficult. Also, assume that previous on-site inspections suggest that the tidal zone will exhibit greater temporal and spatial variability in organism abundance than the subtidal zone.

Let the maximal observed value of MSE of 0·823 be used for the tidal zone monitoring program and an average value of MSE of 0·295 be employed for the subtidal areas. Figure 2d indicates that values for *bcde* of 40 and 110 will be required to detect a 33% reduction in species abundance on subtidal and tidal monitoring programs, respectively.

For the subtidal zone study, one possible design would be $bcde = 1 \times 6 \times 4 \times 2 > 40$. This design requires bimonthly sampling of four station pairs in two relative positions around the NPP. Another possible design would be $bcde = 1 \times 4 \times 5 \times 2 = 40$ which would require seasonal sampling of five station pairs in two locations about the NPP site. The choice of the proper design should depend on the limitations on the study and the proposed effects of the impact.

The value of $bcde = 110$ apparently needed for the tidal zone study exceeds the largest monitoring design for benthic studies investigated by this paper ($bcde = 1 \times 6 \times 5 \times 2 = 60$) when limitations of sampling frequency and depth are imposed. These limitations include taking, at most, bimonthly benthic samples to reduce serial correlation; moreover, all benthic samples must be taken at one depth, the bottom. Referring back to Figure 2d, the smallest detectable difference that a monitoring program with MSE=0·823 can achieve when $bcde = 60$ is a 43% reduction in density. Therefore, either the quantitative objectives of the monitoring program have to be reconsidered in view of the large experimental error expected, or alternative designs must be devised.

Increasing the sampling frequency to monthly intervals would provide the level of detectability desired with $bcde = 1 \times 12 \times 5 \times 2 = 120$ but would likely increase the serial correlation among successive observations. An alternative approach would be to increase the number of station pairs beyond the value of $d = 5$. After the pre-operational phase is complete, the value of MSE can be calculated and the number of station pairs adjusted. If the observed MSE is below the value of 0·823 used to estimate the size of the monitoring program, the number of station pairs can be reduced accordingly. Those station pairs which "track" each other the least should be eliminated. When elimination of station pairs is indicated, such reductions should maintain the properties of othogonality and balance in the monitoring design. For example, if a station pair at the 20 m depth contour is to be eliminated, the corresponding station pair in the other side of the NPP at the same contour depth should be removed to maintain orthogonality. Balance is maintained by omitting from the analysis the pre-operational data for the station pairs discontinued.

5. Conclusion

The ability of a monitoring program to assess changes in the abundance of biota resulting from NPP impacts is largely dependent upon the monitoring design employed. The use of CTP designs has three distinct advantages over traditional unpaired designs frequently used in monitoring studies. These advantages are the following.

(1) Ability to relate changes in biota to the operation of nuclear power plants.

(2) Allows repeated observations of a control–treatment combination between years to be designated as replications.

(3) Reduces the experimental error associated with the monitoring study when favorable control–treatment station pairing is achieved.

The detection of differences in biota between control and treatment stations or between the pre-operational and operational phases is insufficient evidence alone for assessment of impact to NPP operations. The CTP design, however, by comparing the proportional abundance of organisms at control to treatment stations between pre-operational and operational periods, can establish a relationship between biota changes and NPP operations. The validity of the inference is dependent on the assumption that control and treatment stations "track" one another and on the proper choice of data transformation.

Unpaired monitoring designs cannot generate true replicate observations because of the inherent spatial and temporal heterogeneity of aquatic systems. Replicate observations are generally assumed to be samples from a single population with constant mean and variance. With proper station pairing using the CTP designs, temporal effects are eliminated from the data allowing successive annual observations to be considered as replicates. It is this plots-treated-alike variance (Eberhardt, 1978) that is needed to test for ecological impact.

McKenzie *et al.* (1977) compared the analysis of zooplankton data from NPP studies using both CTP designs and comparable unpaired experimental designs. He found up to a seven-fold reduction in the experimental error (MSE) associated with the use of CTP designs. Greater sensitivity to changes in abundance resulting from NPP impacts may be obtained by the use of CTP designs for an equivalent amount of monitoring effort.

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