# DESIGN ISSUES IN ENVIRONMENTAL SURVEYS

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## 1. Introduction

A variety of design issues are somewhat unique to environmental surveys. This paper discusses some of these issues and illustrates them with several environmental surveys recently designed by Research Triangle Institute (RTI). Section 2 provides a short description of the basic illustrative surveys; other examples are given as necessary to illustrate particular points. Section 3 discusses issues related to sampling error and Section 4 deals with non-sampling error issues. Section 5 provides a brief discussion and summary.

## 2. Description of illustrative surveys

This section provides examples of different types of environmental surveys in which RTI has been involved. These surveys will be used to illustrate the issues discussed in the next sections. Section 2.1 describes the National Pesticide Survey, a nationwide survey of drinking water wells designed to investigate the presence of pesticides in water from private wells and from community water systems using well water. Section 2.2 describes the National Radon Survey, designed to estimate the frequency distribution of radon concentrations in residential structures in the United States. Section 2.3 describes the National Indoor Air Quality Study, designed to estimate the prevalence of a variety of indoor air pollutants in U.S. homes. Section 2.4 describes the Total Exposure Assessment Methodology (TEAM) study, whose focus is on personal exposure to volatile organic compounds.

### 2.1 National Pesticide Survey

The principal objectives of the National Pesticide Survey (NPS) are (a) to determine the frequency and concentration of pesticide contamination in the drinking water wells of the nation, and (b) to determine how pesticide contamination correlates with patterns of pesticide usage and with groundwater vulnerability.

A precise definition of the target population for the study is all operating community system wells and rural wells that provide water for domestic use. (Systems that obtain water exclusively from surface water sources are excluded.) Two survey components are thus identified, Component-I consisting of (rural) domestic wells and Component-II of community systems. Separate sampling frames and sampling designs are used in the two components.

For Component-II, a list of community systems is available from the Federal Reporting Data System (FRDS) for use as sampling frame. For Component-I, however, no list exists and a multi-stage area sampling design was implemented.

### 2.2 National Radon Survey

Primary objectives of the National Radon Survey (NRS) are (a) to determine the frequency distribution of radon concentrations in U. S. homes, and (b) to investigate relationships between radon levels in home and parameters related to geology, geography and house characteristics (Cox et al., 1986).

The target population for the study is all housing units that serve as principal residences and are continuously occupied during the monitoring period. Excluded are vacant, seasonal and occasional use structures.

Two data collection methods are feasible for the NRS, differing by the form of the first interview: by telephone or face-to-face. In either case, collection of radon detectors is by mail. The face-to-face mode allows for detector placement by the field interviewer while the telephone mode requires placement by the respondent.

### 2.3 National Indoor Air Quality Study

The main objectives of the National Indoor Air Quality Study (NIAQS) are to determine the existing levels of specified pollutants in residences and to estimate their ultimate health effects (Iachan and Whitmore, 1986). Three basic groups of pollutants monitored are volatile organic compounds (VOCs), combustion products and formaldehyde.

The target population for the study consists of all occupied dwelling units in the nation, excluding group quarters, dormitories, institutions, barracks and all other temporary occupancy units. The permanent occupancy restriction is important in order to assess extended exposure and hence approximate lifetime exposure.

The statistical design must permit estimation of average annual concentrations of target pollutants. In addition, seasonal effects in concentration levels are of interest. Issues related to sampling in space and time are discussed in Section 3.

### 2.4 Total Exposure Assessment Methodology Study

The Total Exposure Assessment Methodology (TEAM) Study had among its primary goals (a) to develop methods to measure individual total exposure--through air, food and water--to toxic and carcinogenic chemicals, and (b) to apply these methods to estimate the exposures of U. S. urban populations (Wallace et al., 1987). Selected urban sites included in the study were two New Jersey cities and two urban areas in California. Small comparison studies were also undertaken in a North Carolina city and a rural town in North Dakota. The most recent TEAM study was conducted in Baltimore. Naturally, the data obtained in these studies cannot be expected to be representative of all U. S. cities.

The TEAM studies present some problems similar to those arising in the previously described surveys. The temporal effects problem may be less important than for the NIAQS and the NRS due to the personal nature of the measurements. For the same reason, however, the measurements are even more intrusive. The likely impact of intrusive measurements on response rates is discussed in Section 4.

## 3. Sample design issues

### 3.1 Auxiliary information

Auxiliary information is typically used in surveys to provide disproportionate representation in the sample to population subgroups of particular interest and to enhance survey efficiency--usually stated as maximizing survey precision for a given cost. More generally, auxiliary information may be used to reduce sampling and non-sampling errors. Reduction of sampling error may be achieved, for example, by means of effective stratification and oversampling. An example of the use of auxiliary information to reduce non-sampling errors is for nonresponse bias adjustments. Auxiliary variables improve survey accuracy to the extent that they are correlated with key survey variables.

Environmental surveys usually employ multi-stage stratified sample designs that make use of auxiliary variables in several ways. When area household sampling is used, population-related measures (such as number of occupied housing units and socio-economic status) may be utilized at the initial stages of sampling. In addition, strata are formed that correspond to relevant reporting domains (i.e., subgroups for which estimates are desired). A good example is geographic regions since regional breakdowns of survey results are generally desired.

When useful auxiliary information is not available in the sampling frame, collecting such background data in the first phase of a two-phase sample may be worthwhile. These data may then be used to efficiently stratify the second-phase sample (e.g., homes or persons to be monitored). A two-phase sample design is particularly convenient when a screening interview may be necessary to identify survey eligibles; in this case, the screening sample coincides with the first-phase sample. Another use of two-phase sample designs (or double sampling) in environmental surveys is related to the typically high unit cost associated with laboratory measurements. Less expensive, and possibly less intrusive, measurements may be made for the first-phase sample, and more expensive and precise measurements for the second-phase (sub)sample. Regression estimates (based on the double sample) may then be computed whose precision increases with the correlation between the measurements made in the two phases.

Among variables most useful in the design of environmental surveys are those related to potential sources of the pollutants or chemicals of interest. When groundwater contamination by pesticides is the primary focus of the survey, as is the case for the National Pesticide Survey (NPS), it seems sensible to consider two basic characteristics: some measures of pesticide usage in the vicinity of the groundwater source and of vulnerability of the groundwater to such contamination. An index of groundwater vulnerability-- the DRASTIC index-- is discussed in Section 3.2.

For indoor air quality surveys, such as the NIAQS, potential sources will of course depend on the particular chemicals of primary interest. While for combustion products, the presence of gas stoves, kerosene heaters, woodstoves and the like is of essential value, interest on specific chemicals may vastly increase the number of auxiliary variables of potential usefulness. For instance, if formaldehyde is one of the target compounds for the survey, a gamut of household furnishings ranging from carpets to plywood may be associated with formaldehyde levels.

On the other hand, the presence of radon in the home environment is believed to be highly correlated with geologic characteristics of the site (soil), emanating from natural rather than man-made sources. Radon concentrations are also influenced by house construction characteristics, ventilation, etc. Discussion of how the design may capitalize on such covariates, and also allow for inferences concerning their relationship with radon levels, is given in the next subsections.

When personal exposure is the main focus of the survey, as in the TEAM studies, person-related characteristics will, if used in the design, further improve its efficiency. Personal characteristics relevant for exposure to chemicals include smoking status and occupation. As noted later, the TEAM measurements include both overnight and daytime integrated measurements, each of which affected by different environmental characteristics.

### 3.2 Stratification

Common reasons for stratification are improving the precision of survey estimates and ensuring adequate precision for domains of interest. Better precision, i.e., smaller sampling variance, is achieved for key survey estimates by forming homogeneous strata so that the within-stratum variation is small and the between-stratum variation is large. In addition, some control over the sample distribution is ensured by stratification. In conjunction with two-phase sampling, stratification also permits the identification of members of subpopulations of special interest that can then be sampled at higher rates.

These issues are discussed next for the illustrative surveys described previously. The National Pesticide Survey (NPS) Component-I, the National Radon Survey (NRS) and the National Indoor Air Quality Study (NIAQS) present similar issues for first-stage stratification; first-stage units (FSUs) for all three surveys are counties or county equivalents.

First-stage stratification for the two components of the National Pesticide Survey (NPS) was by pesticide use and groundwater vulnerability, based respectively on the total volume (or weight) of pesticide used per unit county area and on a hydrogeologic index (Aller et al., 1985). For Component -I, geographic strata consisting of counties that are not necessarily contiguous were based on the groundwater vulnerability (DRASTIC) index, a weighted average of the following variables:

- depth to groundwater,
- net recharge,
- aquifer media,
- soil media,
- topography, primarily slope,
- impact of vadose zone,
- hydraulic conductivity of the aquifer.

For the National Radon Survey (NRS), regional strata were based on 13 geologic, groundwater regions developed by Heath (1984) and on structural and lithologic boundaries shown in Bayer's (1983). Ten regional strata were constructed by grouping contiguous counties; some of these regions were quite small population-wise and were later collapsed to yield 8 primary regions (Cox, et al., 1986)..

For the National Indoor Air Quality Study (NIAQS), four geographic strata were formed for the basic purpose of imposing geographic and temporal control over the sample. The four geographic strata shown in Exhibit 1 were constructed by partitioning the two primary regions, East/West, into strata of about equal number of occupied housing units. An additional concern was that the ten EPA regions should not be split, i.e., cross stratum boundaries.

First-stage units (FSUs) for the TEAM study were blocks, block groups, enumeration districts (EDs), or combinations thereof as defined by the U. S. Bureau of the Census. First-stage stratification within each study site was by geographic location and by socio-economic status (SES). An SES index developed by RTI uses block-level (or ED-level) average values of several variables included in the Census data.

In the TEAM studies, the third-stage sample of individuals selected for personal exposure monitoring was stratified based on data collected in a screening interview conducted for each participating household. Screening information used for stratification included smoking status and occupation, so that smokers and persons with potentially high exposure levels could be oversampled. Such oversampling strategy permits more accurate estimation of the exposure distribution (upper percentiles).

3.3 Sample design optimization

This section discusses optimal two-stage area household sample designs for environmental surveys. Optimization is in the sense of minimum survey cost under variance constraints, or of minimum variance for fixed cost. For simplicity, one single variance is considered; in this case, an explicit solution may be obtained whereas in general an optimization routine needs to be performed.

The sampling variance of an estimated mean, proportion or total may be written in the form

$$V = \frac{\sigma_1^2}{n_1} + \frac{\sigma_2^2}{n_1 n_2} \qquad (3.1)$$

for a two-stage random sample with $n_1$ first-stage units (FSUs) and $n_1 n_2$ second-stage sample units (SSUs). Note that $n_2$ is the average number of SSUs per sample FSU, and also that $\sigma_1^2$ and $\sigma_1^2$ are respectively the between-FSU and within-FSU variance components.

A cost model of the form

$$\text{Cost} = c_0 + c_1 n_1 + c_2 n_1 n_2 \qquad (3.2)$$

will be assumed where

- $c_0$ is independent of the number of sample FSUs and SSUs selected,
- $c_1$ is the unit cost per sample FSU (or segment),
- $c_2$ is the cost associated with each sampled person/home.

Two of the primary components of the FSU cost, $c_1$, are:

(a) Counting and listing costs;
(b) The portion of screening costs associated with traveling to segments.

Primary components of the SSU cost, $c_2$, are:

(a) The portion of screening costs associated with households;
(b) Interviewing costs;
(c) Monitoring and chemical analysis costs per sample home/person.

By minimizing the variance (3.1) subject to a fixed cost (3.2), we obtain the optimum

$$n_2^* = \sqrt{\frac{1-\rho}{\rho}} \sqrt{\frac{c_1}{c_2}}$$

where the intracluster correlation, $\rho$, is defined as $\rho = \sigma_1^2 \div (\sigma_1^2 + \sigma_2^2)$.

We expect that the effect of low intracluster correlations, i. e., large ratios $(1-\rho) \div \rho$, will be compensated to some extent by very small $c_1/c_2$ ratios. Unlike other types of surveys, the cost ratio, $c_1/c_2$, tends to be small (e.g., between 0.10 and 0.50) due to the large measurement costs associated with chemical (lab) analyses.

Exhibit 2 presents some values of the optimal number of sample second-stage units (SSUs) per cluster (FSU), $n_2^*$, for different values of the intracluster correlation, $\rho$, and cost ratio, $c_1/c_2$. The intracluster correlation may be estimated based on available data.

3.4 Temporal dimension

Environmental surveys present an essentially unique problem of time-dependent survey measurements. Special precautions must then be taken in survey design to account for this factor so as not to confound temporal differences with other effects of interest.

Good examples of seasonal effects are provided by the National Radon Survey (NRS) and by the National Indoor Air Quality (NIAQS); in both these surveys, concentration measurements tend to be higher in the winter season, when doors and windows are typically kept closed. Concentrations of major outdoor air pollutants (e. g., CO and $SO_2$) generally peak in the winter as well. Compounds investigated in the TEAM study show a similar seasonal pattern, as illustrated in Exhibit 3.

An example of personal exposure study where temporal sampling was used is the Washington, D. C., and Denver CO Study. Since CO exposures are highly day-dependent, with strong weekday vs. weekend differences, a 3-day monitoring period was randomly selected for each sample subject (who could choose one of the three days for monitoring). A similar procedure was used in the Non-Occupational Pesticide Exposure Survey (Lev-On et al., 1987).

We illustrate below the problem and implications, as well as the design measures taken to prevent them, with the NIAQS. While day-of-week effects may be attenuated in the NIAQS by having measurements integrated over a 7-day period, the NRS can overcome seasonal effects by using a 12-month intergrated measuring device, the alpha-track monitor (Cox, et al., 1985).

Another example where seasonality is of concern deals with groundwater sampling for pesticide contamination (see, e. g., Iachan and Whitmore, 1987). Such contamination tends to be stronger in the growing season. Some groundwater studies sampled different strata in successive months, and inferences concerning stratum comparisons were made without accounting for the time dimension. In such studies, stratum differences were in fact confounded with temporal differences.

In the NIAQS, data were to be collected in succession on 50 first-stage units selected from two primary regional strata, East and West, in a time period of approximately two years. Two independent samples of 25 FSUs were selected from the two regions, to be fielded one-FSU-a-month for a total of 25 months of data collection. Two data collection teams were available, one for each region, so that two FSUs could be covered simultaneously each month, one FSU in each region.

This approach provided some limited geographic/temporal control over the sample in the sense that no month included data collected in only one regional stratum. To the extent that seasonal characteristics differ within each of these two large regions, however, the confounding and biasing danger still existed--it was possible that only FSUs in the South, for example, would have data collected in the Winter. To avoid this risk, and the associated bias problems, further geographic control was imposed over the sample with the following assignments of FSUs to time periods (months).

The two primary regional strata were each partitioned into two strata (essentially north/south), as shown in Exhibit 1, with twelve or thirteen FSUs assigned to each of the four strata. The 25 FSUs in each primary region were then assigned to data collection periods alternating between each stratum in successive periods, as represented in Exhibit 4. A restricted randomization procedure was developed for the assignment that ensures that none of the four strata will have data collected in any two successive months.

## 4. Non-sampling error issues

### 4.1 Nonresponse

Many environmental surveys involving human populations present especially acute nonresponse problems. The severity of the nonresponse problem is associated in part with the intrusiveness or inconvenience of the measurement devices. Sizable monitors may be placed in the home, as in the NIAQS, or personal monitors may be carried by the participants, as in the TEAM studies. Respondent burden is often further compounded in environmental surveys by the requirement that activity pattern (e.g., diary) data be collected, particularly in personal exposure surveys. Response bias will occur to the extent that the response rate is correlated with survey variables (e.g., exposure).

Focus groups conducted in the design phase of the NIAQS strongly suggested that the monitors should be quiet and compact (Iachan, et al., 1986). Redesigning measurement instruments is likely to bemore effective than response enhancement measures such as(monetary incentives. Among response enhancing procedures evaluated by the focus group discussions conducted by RTI (Iachan, et al., 1986), providing participants with the results of their home and/or personal exposure measurements seemed particularly important.

Exhibit 5 illustrates the magnitude of the nonresponse problem with the New York Air Study (Task II) response rates. This random-digit-dialing (RRD) sample survey was conducted for the New York State Energy Research and Development Authority (see Cox and Jones, 1988, for details). Task II of the New York Air Study involved 3-month and 12-month integrated radon measurements, and the respective overall response rates (shown in the exhibit) are 30% and 25%. These response rates, computed as the number of valid measurements divided by the total number of residential telephone numbers identified, still do not take into account the "hit rate" associated with the first step where working residential telephone numbers were identified (the hit rate was about 35% in this case).

Survey design can play an important role in minimizing the impact of nonresponse, both by reducing the overall level of nonresponse, and by providing a basis for analytical treatment of the nonresponse that occurs. Good survey design will take into account the response characteristics of the target population, and may incorporate data collection techniques such as multiple callbacks, nonresponse followup subsampling, or monetary incentives, to increase response rates. Characteristics of the sample design can influence the way in which nonresponse is treated. For example, cluster sampling may make multiple callbacks an economically viable option for a survey. If a particular subgroup of the target population is known to have low response rate, the sampling design may call for oversampling of that subgroup to ensure that an adequate number of completed responses are obtained for the subgroup.

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Exhibit 1. NIAQS Geographic Strata

| Geographic Stratum | States | Geographic Stratum | States |
|---|---|---|---|
| Stratum I (East) | | Stratum II (West) | |
| A | ME | C | MI |
| | VT | | IN |
| | NH | | IL |
| | MA | | WI |
| | RI | | MN |
| | CT | | IA |
| | | | MO |
| | | | KS |
| | NY | | NE |
| | NJ | | |
| | PA | | |
| | DE | | |
| B | MD | D | AR |
| | DC | | LA |
| | VA | | OK |
| | WV | | TX |
| | | | NM |
| | | | CO |
| | NC | | UT |
| | SC | | WY |
| | GA | | SD |
| | FL | | ND |
| | AL | | MT |
| | MS | | CA |
| | TN | | NV |
| | KY | | AZ |
| | | | IA |
| | | | WA |
| | | | OR |

Exhibit 2. Optimum Number of Sample Homes Per Segment, $n_2$, for Various Values of the Intracluster Correlation ($\rho$) and Cost Ratio ($c_1/c_2$)

| $\rho$ | $c_1/c_2$ | | | |
|---|---|---|---|---|
| | 0.10 | 0.50 | 1.00 | 2.00 |
| 0.01 | 3 | 7 | 10 | 14 |
| 0.02 | 2 | 5 | 7 | 10 |
| 0.04 | 2 | 3 | 5 | 7 |
| 0.05 | 1 | 3 | 4 | 6 |

Exhibit 3. Team 24-hour Personal Exposure to Tetrachloroethylene Compared to Outdoor Air in New Jersey (First Three Seasons).

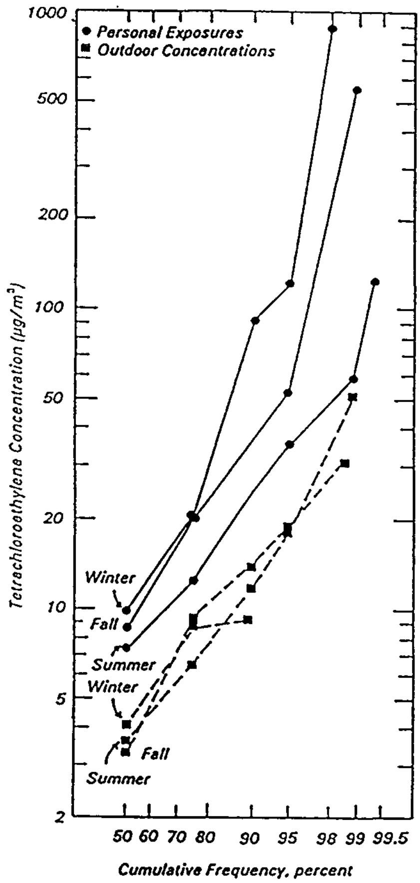

Exhibit 4. Restricted Random Assignment of FSUs to NIAQS Data Collection

| Regional Stratum | | Period 1 | 2 | 3 | 4 | 5 | ... | 24 | 25 |
|---|---|---|---|---|---|---|---|---|---|
| I (East) | A | X | | X | | X | | | X |
| | B | | X | | X | | ... | X | |
| II (West) | C | | X | | X | | ... | X | |
| | D | X | | X | | X | | | X |

Exhibit 5. New York Air (Task II) Response Rates

| | Number | Percent | Cum. Percent |
|---|---|---|---|
| Residential Nos. Identified | 7,678* | - | - |
| Interviews with Eligibles | | | |
| Attempted | 4,147 | 54% | 54% |
| Completed | 3,813 | 92% | 50% |
| Cooperating Nonmovers Receiving Monitors | 3,115 | 82% | 41% |
| Valid Measurements | | | |
| 3-month | 2,267 | 73% | 30% |
| 12-month | 1,930 | 62% | 25% |

* Out of 21,813 telephone numbers called, this reflects a 35.2% hit rate obtained with the Mitofsky-Waksberg RDD method.