Journal of Official Statistics
Vol. 5. No. 4, 1989, pp. 323–335

Issues in Environmental Survey Design

Ronaldo Iachan[1]

Abstract: Several environmental survey design issues are discussed and illustrated with surveys designed by Research Triangle Institute statisticians. Issues related to sampling and nonsampling errors are illustrated for indoor air quality surveys, radon surveys, pesticide (well-water and groundwater) surveys, and occupational and personal exposure surveys. Sample design issues include the use of auxiliary information, (e.g., for stratification), and sampling in time. We also discuss the reduction and estimation of nonsampling errors, including nonresponse and measurement bias.

Key words: Environmental surveys; sample design; nonsampling errors.

1. Introduction

Environmental surveys involve a variety of sample design issues, some of which are not generally faced in other types of surveys. We discuss some of these issues and draw examples from several environmental surveys recently designed by the Research Triangle Institute (RTI).

Environmental surveys are highly diverse and are most easily classified by the type of target population element (and ultimate sampling unit). While some surveys have residential structures (e.g., homes) as elements, others are interested in measurements on individuals (e.g., personal exposure surveys) and still others involve measurements on more or less "natural" elements, or environmental media (see, e.g., Polfeldt and Justusson (1983)) such as rivers, outdoor air, groundwater wells, etc. In addition, some surveys may be interested in nonresidential structures (e.g., "sick buildings"), others in particular types of commercial or industrial establishments and so on.

The examples selected here illustrate a variety of design issues. Section 2 provides a short description of the surveys used as examples. Section 3 discusses issues related to survey precision (i.e., considers sampling errors) and Section 4 deals with nonsampling error issues. Section 5 provides a brief discussion and summary.

2. Description of the 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 Sections 3 and 4. 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.

[1] Research Triangle Institute, Box 12194, Research Triangle Park, North Carolina 27709, U.S.A.

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, which focuses on personal exposure to volatile organic compounds.

It should be pointed out that due to scarcity of funds, the NIAQS has not been conducted to date. Nevertheless, the prototype design briefly described in this paper has been used in similar, but smaller surveys.

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 (super-strata) are 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 a sampling frame. For component I, however, no list exists and a multistage area sampling design was implemented. Design issues for this survey are discussed in Section 3.

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 homes and parameters related to geology, geography and house characteristics (Cox et al. (1986)).

The target population for the study is all U.S. 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: telephone or face to face. In either case, collection of radon detectors is by mail. The face to face mode allows the interviewer to install the detector while the telephone mode requires the respondent to install the detector.

The choice of data collection strategy also effects the sample design, as discussed in Section 3.

2.3. National Indoor Air Quality Study

The main objectives of the National Indoor Air Quality Study (NIAQS) are (a) to determine the existing levels of specified pollutants in residences and (b) 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. As for the NRS, 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 Study (TEAM) had among its primary goals (a) to develop methods to measure individual total exposure – through air, food and water – to toxic carcinogenic chemicals, and (b) to apply these methods to estimate the exposures of U.S. urban populations. Selected urban sites included in the study were two cities in New Jersey and two urban areas in California (Hartwell et al. (1987)). Smaller studies were also undertaken in a city in North Carolina and a rural town in North Dakota. The most recent TEAM study was conducted in Baltimore, MD. 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 surveys described earlier. The temporal effects problem may be less important for the TEAM studies than for the NIAQS, and possibly the NRS, due to the personal nature of the measurements. For the same reason, however, the measurements are even more intrusive. The likely effect of intrusive measurements on response rates is discussed in Section 4.

3. Sample Design Issues

This section discusses sampling error in environmental surveys. Often the sample can be optimally designed from a sampling error perspective. Here optimization is defined as minimum survey cost under variance constraints, or minimum variance for fixed cost. In general, an optimization routine should be performed whenever multiple precision requirements are considered. Optimal designs for the detection of ecological or biological change in environmental monitoring are discussed by Millard (1987). Rather than minimizing the variance, their approach is based upon maximizing the power for a fixed cost (or conversely, minimizing the cost for a fixed power), similar to that considered by Bernstein and Zalinsky (1983).

3.1. *Auxiliary information*

Auxiliary information is typically used in surveys (a) to provide (disproportionate) sample representation to certain population subgroups and (b) 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 nonsampling errors. Reduction of sampling error (i.e., sampling variance of survey estimates) may be achieved, for example, by means of effective stratification and oversampling. Nonresponse bias adjustments are an example of the use of auxiliary information to reduce nonsampling errors. These auxiliary variables are believed to be highly correlated with key survey variables which leads to improved survey accuracy.

Environmental surveys usually employ multistage 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) are used at the initial stages of sampling. In addition, strata corresponding to reporting domains (i.e., subgroups for which estimates are desired) of interest are formed. A good example is geographic regions since regional breakdowns of survey results are generally desired.

When useful auxiliary information is not available on the sampling frame, collecting background data in the first phase of a two-phase sample may be worthwile. 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, in any case, when a screening interview may be necessary to identify survey eligibles; in this case, the screening sample coincides with the first-phase sample. Table 1 summarizes the various uses and sources of auxiliary data in survey design and analysis.

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 sample or subsample. Regression estimates (based on the double sample) may then be computed; the precision of these estimates 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. We will illustrate these potential sources for the surveys described in the previous section. The specific use of these variables in the survey design will be discussed in the next subsections.

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 measure 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 chemicals of interest. A single chemical can have a large number of potential sources. For combustion products, the presence of gas stoves, kerosene heaters, woodstoves, and the like is important (see Table 2) and a gamut of household furnishings ranging from carpets to plywood may be associated with formaldehyde levels.

Table 1. Auxiliary information levels

Types (Levels)		Use
Available in the frame		Phase 1 stratification
Collected in phase 1	(screening) interview	Phase 2 stratification
Collected in phase 2	interview	Data analysis (including nonresponse adjustments)[1]

[1] Information collected at each level may of course be used at subsequent levels (e.g., all three levels of information may be used in the analysis).

Table 2. Potential sources for combustion products

Sources	CO	NO_2	Particulates
Kerosene heater	X	X	X
Woodstove (fireplace)	X		X
Gas stove	X	X	
Tobacco (smokers)	X		X
Dryer	X	X	
Garage (attached)	X	X	X

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, however, by house (construction) characteristics (e.g., ventilation, etc.). A discussion of how the design may utilize 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 efficiency. Personal characteristics relevant for exposure to chemicals include use of tobacco products and occupation. As noted later, the TEAM measurements include both overnight and daytime integrated measurements, each of which are affected by environmental characteristics.

3.2. *Stratification*

Design stratification is considered in environmental surveys for a variety of reasons. Stratification is usually used to improve the precision of survey estimates and to ensure 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. Other advantages of stratification are discussed, for example, in Polfeldt and Justusson (1983).

Among the surveys discussed here, the National Pesticide Survey (NPS) component I, the National Radon Survey (NRS), and the National Indoor Air Quality Study (NIAQS) present similar problems 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 based on the total volume or weight of pesticide used per unit county area and on a hydrogeologic index which measures groundwater vulnerability (Aller, Bennett, Lehr, and Pelly (1985)). Table 3 presents stratum sizes for the two survey components, keeping in mind that while FSUs for component I are U.S. counties, FSUs for the single-stage component II sample are community water systems.

For component I of the NPS, geographic strata consisting of counties that are not necessarily contiguous were based on a groundwater vulnerability (DRASTIC)

Stratification for the NPS

Table 3a. Stratification of rural domestic wells[1] (component I)

Pesticide use	Groundwater vulnerability High (#)	High (%)	Medium (#)	Medium (%)	Low (#)	Low (%)	Totals (#)	Totals (%)
High	455	3.5	916	7.0	440	3.4	1811	13.9
Medium	684	5.2	1417	10.8	671	5.1	2772	21.1
Low	1154	8.8	2270	17.3	1170	8.9	4594	35.0
Uncommon	1043	8.0	1894	14.4	997	7.6	3934	30.0
Totals	3336	25.5	6497	49.5	3278	25.0	13,111	100.0

[1] Stratum sizes (#) indicate estimated numbers of wells in thousands.

Table 3b. Stratification of community water systems[1] (component II)

Pesticide use	Groundwater vulnerability High (#)	High (%)	Medium (#)	Medium (%)	Low (#)	Low (%)	Totals (#)	Totals (%)
High	1310	2.6	2669	5.3	1432	2.8	5411	10.7
Medium	2183	4.3	3352	6.6	2559	5.0	8094	15.9
Low	3578	7.0	7199	14.2	5545	10.9	16,322	32.1
Uncommon	3472	6.8	9511	18.7	7961	15.7	20,944	41.3
Totals	10,543	20.7	22,731	44.8	17,497	34.4	50,771	100.0

[1] Stratum sizes (#) indicate number of community water systems.

index. This index is a weighted average of the following variables: depth to groundwater, net recharge, aquifer media, soil media, topography, primarily slope, impact of vadose zone, and 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 (1983). The resulting ten regional strata, constructed by grouping contiguous counties, are presented in Table 4 (Cox et al. (1986)).

For the National Indoor Air Quality Study (NIAQS), four geographic strata were formed to impose geographic and temporal control over the sample. The restricted randomization procedure used for the assignment of FSUs to data collection periods (further discussed in Section 3.3) ensures that no region will be represented in the sample in successive periods. The four geographic regions were constructed by partitioning two primary, East/West strata into four regional substrata with about equal numbers of occupied housing units (estimated using 1980 U.S. Census figures). An additional concern was that the ten EPA regions should not be split, i.e., cross stratum boundaries. Regional estimates are generally desired for these ten regions used by EPA for regulatory and administrative purposes.

First-stage units for the TEAM study

Table 4. NRS regional strata

Region	Description	Occupied housing units
Pacific Coast Range, Sierra Nevada, and Alaska	Contains complex sedimentary, igneous, and metamorphic rocks derived largely from oceanic crust. With the exception of Alaska, the area has relatively few uranium occurrences.	9,147,578
Columbia Lava Plateau and Hawaii	High rolling plateaus (or islands in Hawaii) underlain by extensive basalt lava flows.	1,384,695
Northeast and Superior Uplands	Glacial deposits overlying ancient crystalline rocks.	7,949,428
Colorado Plateau and Major Wyoming Basins	Thin soils overlying consolidated sedimentary rocks. The region includes about 90% of U.S. uranium production through 1979.	332,759
High Plains and Non-glaciated Central	Consolidated, fractured sedimentary rocks.	14,925,794
Atlantic and Gulf Coastal Plain and Southeast Coastal Plain	Flat plains comprised of complexly interbedded sediments and, in some areas, semiconsolidated carbonate rocks.	16,413,141
Glaciated Central	Glacial deposits overlying fractured sedimentary rocks.	20,260,102
Piedmont and Blue Ridge	Thick residual soils overlying fractured crystalline and metamorphosed sedimentary rocks.	6,000,683
Basin and Range	Thick alluvial deposits in basins bordered by mountains.	2,535,297
Southern Rockies and Northern Colorado	Largely mountaineous area containing major outcrop areas of plutonic rocks, many of which are known to be uraniferous. Also includes the Black Hills area of South Dakota.	1,440,196

were city 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 files. These SES-related variables include median housing unit (HU) value and rent, and percent of HUs with complete plumbing (see, e.g., Benrud (1988)). Second-stage sampling units for the TEAM study were households from which persons were selected at the third stage.

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 tobacco use 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 especially the upper percentiles. Table 5 illustrates one occupational categorization into two (high/low) strata of suspected occupational exposure (Pellizzari et al. (1986)).

3.3. *Temporal effects*

Unlike most other surveys, environmental surveys often have 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.

Good examples of seasonal effects are provided by the National Radon Survey (NRS) and by the National Indoor Air

Table 5. TEAM occupational exposure strata

Description	
Stratum I:	High occupational exposure
	Painter or employee in a paint factory or paint shop
	Service station employee, gasoline dispenser
	Auto or airplane mechanic or garage worker
	Furniture repair, refinishing, or stripping worker
	Chemical plant worker
	Petroleum plant worker
	Dry cleaning worker
	Plastics plant worker
	Textile mill worker
	Paper mill or wood processing worker
	Household cleaning worker
	Photo developer
	Landscape worker, gardener
	Pesticide or herbicide applicator
	Taxi/bus/truck/crane/heavy equipment operator
	Maintenance worker or custodian
	Chemistry lab technician or chemist
	Toll collector
	Other exposed (Aviation fuel dispenser, airport ground crew worker, plumber)
Stratum II:	Low occupational exposure
	Other unexposed occupation
	Retired/disabled
	Unemployed
	Housewife/househusband
	Full-time student

Quality Survey (NIAQS). In both of these surveys, concentration measurements tend to be higher in the winter season, when doors and windows are kept closed. Concentrations of major outdoor air pollutants (e.g., CO and SO_2) generally peak in the winter as well. Another example where seasonality has an effect is in groundwater sampling for pesticide contamination (see, e.g., Iachan and Whitmore (1987)). Such contamination tends to be stronger in the growing season. Some state groundwater studies we have reviewed sampled different strata in successive months, and inferences concerning stratum comparisons were made without accounting for time effects. In such studies, stratum differences were in fact confounded with temporal differences.

An example where such potential confounding was considered in the design is the airborne asbestos monitoring study discussed in Iannacchione, Williams, and Lentzen (1984). The study involved sampling day-location points for the presence and concentration of asbestos particulates in the ambient air in various buildings. The measurement devices used in the study allowed the compositing (or integration) of a series of ten successive day-location measurements taken by the same instrument.

Examples of personal exposure studies where temporal sampling was used are the Washington, D.C., and Denver Carbon Monoxide (CO) Study. Since CO exposures are highly day-dependent, a three-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)). It is worth noting that such studies involve measurements with strong weekday vs. weekend differences.

While the NIAQS measurements are mostly integrated during a seven-day period, the NRS can overcome seasonal effects by using a twelve-month integrated measuring device, the alpha-track monitor (Cox et al. (1986)). 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 strata, so that in each stratum, data for a different FSU are collected each month over the 25-month data collection period. Two data collection teams were available, one for each primary stratum, so that two FSUs could be covered simultaneously each month, one FSU in each stratum.

This approach provided some geographic and temporal control over the sample in 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 first partitioned into two (essentially north/south) regions each, with twelve or thirteen FSUs assigned to each of the four regions. The 25 FSUs in each primary stratum were then assigned to data collection periods alternating between each region in sucessive periods, as represented in Table 6. A restricted randomization procedure was developed for the assignment that ensures that none of the four regions will have data collected in any two successive months.

Table 6. 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

4. Nonsampling Error Issues

4.1. Nonresponse

Many environmental surveys involving human populations present 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 group sessions conducted in the design phase of the NIAQS strongly suggested that the monitors should be quiet and compact (Iachan, Pate, Sebestik, and Whitmore (1986)). Redesigning measurement instruments is likely to be more effective than response enhancement measures such as monetary incentives. Among response enhancing procedures evaluated by the discussions conducted by RTI (Iachan et al. (1986)), providing participants with the results of their home and personal

Table 7. Response rates: All TEAM sites

	New Jersey	North Carolina	North Dakota	Los Angeles	Antioch/ Pittsburg
Households screened	5578	307	104	1260	604
Eligible households	5208	295	91	1219	561
Screening completed	4426	280	87	1063	502
	(85%)	(95%)	(96%)	(87%)	(89%)
Persons					
Selected	852	33	45	190	121
Eligible	693	30	36	182	111
Completed study	355	24	24	117	71
	(51%)	(80%)	(67%)	(64%)	(64%)
Overall response rate[1]	44%	76%	64%	56%	57%

[1] Overall response rate = Screening rate × completion rate.

Table 8. New York Air (Task II) response rates

	Number	Percent	Cum. percent
Residential nos. identified	7 678[1]	–	–
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

[1] Out of 21,813 telephone numbers called, this reflects a 35.2% contact rate obtained with the Mitofsky-Waksberg RDD method.

exposure measurements seemed particularly important.

Table 7 illustrates with TEAM response rates the magnitude of the nonresponse problem. The problem is even more apparent for the New York Air Study (Task II) response rates shown in Table 8; this random-digit-dialing (RDD) 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 three-month and twelve-month integrated radon measurements, and the respective overall response rates shown in Table 8 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 contact rate associated with the first step where working residential telephone numbers were identified (the contact rate was about 35% in this case).

Survey design can play an important role in minimizing the effect 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. All surveys discussed in this paper used multiple callbacks to enhance response rates.

Characteristics of the sample design can influence the way in which nonresponse is treated. For example, cluster sampling may make multiple callbacks economically viable for surveys. 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 complete responses are obtained for the subgroup.

4.2. *Measurement error*

The problem of measurement errors in environmental surveys also transcends the usual survey response errors because field and laboratory measurements can introduce uncertainties and biases into survey estimates.

Cost and policy implications of systematic bias cannot be overemphasized. Lucas and Wheeless (1986) illustrate the problem in air or water monitoring studies designed to detect violations of regulatory limits. Underestimation of the total amount of toxic contaminants leads to a corresponding underestimate of the cost of remedial action. Also, negative (positive) measurement biases result in under (over)-estimation of the number of violations.

Lucas and Wheeless (1986) investigate methods for estimating measurement bias, and correcting for the bias survey estimates of the mean. Such methods, involving the use of standard or spiked specimens, have been extended to proportion estimates.

5. Conclusions

The examples in this paper illustrate issues related to the design of environmental surveys. Efficient designs include stratification on variables believed to have reasonably high correlation with survey variables of interest. Particularly useful is stratification at the second phase of a two-phase sample design. Two-phase sampling allows for screening (at the first-phase) for relatively rare (eligible) subpopulation members. Two-phase sample designs are also useful for estimating parameters related to the upper tail (e.g., upper percentiles) of the exposure or contamination distribution.

Environmental survey samples are typically selected with (two-phase) multistage stratified designs; these designs may be optimized with knowledge of relative unit costs and variance components. Optimization routines do not, however, take nonsampling error into consideration, seeking minimum survey cost under sampling variance constraints.

Environmental surveys may, and typically do, entail particularly acute nonsampling error problems. Both nonresponse bias and measurement bias tend to be high. In addition to attempts to reduce nonresponse and measurement errors, several adjustments and corrections for these biases must be adopted.

6. References

Aller, L., Bennett, T., Lehr, J.H., and Pelly, R.J. (1985): DRASTIC: A Standardized System for Evaluating Groundwater Pollution Potential Using Hydrogeologic Settings. U.S. Environmental Protection Agency.

Bayer, K.C. (1983): Generalized Structural, Lithologic, and Physiographic Provinces in the Fold and Thrust Belts of the United States. U.S. Geological Survey, Scale 1 : 2, 500,000.

Benrud, C.H. (1988): SAS Macros for Constructing Sampling Frames Using Area Segment Listing Units That Meet Minimum Size Requirements, With Optional SES Codes. Research Triangle Institute Report.

Bernstein, B.B., and Zalinsky, J. (1983): An Optimum Sampling Design and Power Tests for Environmental Biologists. Journal of Environmental Management, 16, pp. 35–43.

Cox, B.G., Watson, Jr., J.E., Holt, N.A., Daum, K.A., Woodside, M.B., Alexander, W.J., and Singletary, H. (1986): Design of the National Survey of Radon Levels in Residential Structures. Research Triangle Institute Report 3508-17-02S, U.S. Environmental Protection Agency Contract No. 68-01-6826.

Cox, B.G. and Jones, S.M. (1988): Design Issues for Surveys of Radon Levels in Homes. Paper presented at the Survey

Research Section of the American Statistical Association Annual Meetings.

Hartwell, T.D., Pellizzari, E.D., Perritt, R.L., Whitmore, R.W., Zelon, H.S., Sheldon, L.S., Sparacino, C.M., and Wallace, L. (1987): Results from the Total Exposure Assessment Methodology (TEAM) Study in Selected Communities in Northern and Southern California. Atmospheric Environment, 21, pp. 1995–2004.

Heath, R.C. (1984): Groundwater Regions of the United States. U.S. Geological Survey Water Supply Paper 2242.

Iachan, R. and Whitmore, R.W. (1986): Survey Design for the National Indoor Air Quality Survey. Research Triangle Institute Report 3080-41-01F, U.S. Environmental Protection Agency Contract No. 68-01-6826.

Iachan, R. and Whitmore, R.W. (1987): Review of Iowa Groundwater Studies. Research Triangle Institute Report 3886-01-01F.

Iachan, R., Pate, D. K., Sebestik, J., and Whitmore, R. W. (1986): Final Report on Focus Groups Used to Refine the Survey Design for the National Indoor Air Quality Study. Research Triangle Institute Report 3080-43-01F, U.S. Environmental Protection Agency Contract No. 68-01-6826.

Iannachione, V.G., Williams, S.R., and Lentzen, D.E. (1984): Sample Design for Estimating the Mean Concentration of Airborne Asbestos in a Building. Design report prepared for EPA by the Research Triangle Institute.

Lev-On, M., Delwiche, J.C., Lin, C.C., Immerman, F.W., Rush, G.A., Jones, S.M., Camann, D.E., Harding, H.J., and Hsu, J.P. (1987): Non-Occupational Pesticide Exposure Study (NOPES). Interim Report to EPA.

Lucas, R.M. and Wheeless, S.C. (1986): Correcting Population Parameter Estimates for Measurement Bias. Research Triangle Institute Report 2757-06-01F, U.S. Environmental Protection Agency Contract No. 68-01-6826.

Millard, S.P. (1987): Environmental Monitoring, Statistics and the Law: Room for Improvement. The American Statistician, 41, pp. 249–253.

Pellizzari, E. D., Perritt, K., Hartwell, T.D., Michael, L.C., Whitmore, R.W., Handy, R.W., Smith, D., and Zelon, H.S. (1986): Total Exposure Assessment Methodology (TEAM Study): Selected Communities in Northern and Southern California. Research Triangle Institute Report 2391-00-03F, U.S. Environmental Protection Agency.

Polfeldt, T. and Justusson, B. (1983): On Applications of Random Techniques in Environmental Statistics. Statistical Review, Vol. 21, (5), pp. 217–227.

Received July 1988
Revised July 1989