Using a Master Sample to Integrate Stream Monitoring Programs

David P. LARSEN, Anthony R. OLSEN, and Donald L. STEVENS, JR.

The need for aquatic resource condition surveys at scales that are too extensive to census has increased in recent years. Statistically designed sample surveys are intended to meet this need. Simple or stratified random sampling or systematic survey designs are often used to obtain a representative set of sites for data collection. However, such designs have limitations when applied to spatially distributed natural resources, like stream networks. Stevens and Olsen proposed a design that overcomes the key limitations of simple, stratified random or systematic designs by selecting a spatially balanced sample. The outcome of a spatially balanced sample is an ordered list of sampling locations with spatial distribution that balances the advantages of simple or stratified random samples or systematic samples. This approach can be used to select a sample of sites for particular studies to meet specific objectives. This approach can also be used to select a "master sample" from which subsamples can be drawn for particular needs. At the same time, these individual samples can be incorporated into a broader design that facilitates integrated monitoring and data sharing.

Key Words: Stream surveys; Survey designs.

1. INTRODUCTION

In the United States, state and federal agencies are assuming the responsibility to monitor the ecological and commodity-related condition of natural resources under their management through the design and implementation of natural resource surveys, some statistical. These are often colloquially called "status and trends" programs. At the federal level these agencies include the Environmental Protection Agency, the Geological Survey, the Department of Agriculture, the Forest Service, the Fish and Wildlife Service, and the National Oceanic and Atmospheric Administration. At the state level, these include departments of fish and wildlife, forestry, agriculture, and environmental quality. Even if agreement is reached regarding the need to design sound statistical surveys (often it is not), each entity often has agency-specific objectives leading to designs that are independent of other

David P. Larsen is Research Aquatic Biologist, and Anthony R. Olsen is Environmental Statistician, Pacific States Marine Fisheries Commission, c/o Western Ecology Division, National Health and Ecological Effects Lab, Office of Research and Development, U.S. Environmental Protection Agency, 200 SW 35th Street, Corvallis, OR 07333 (E-mail for correspondence: *Larsen.phil@epa.gov*). Donald L. Stevens, Jr., is Associate Professor, Department of Statistics, Oregon State University, Corvallis, OR 97331.

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agency designs although their geographic domains of interest might overlap and some of their condition indicators might be identical. Some agencies have partially resolved this problem by establishing national statistical surveys based on a common statistical design and standard indicators that can be augmented locally or regionally (e.g., Department of Agriculture's National Agriculture Statistical Survey, Forest Service's Forest Inventory and Analysis/Forest Health Monitoring program). Evaluating the condition of aquatic ecosystems has only recently been based on sound statistical survey techniques. And, particularly in the Pacific Northwest, a plethora of agencies are responsible for monitoring stream condition including, at the federal level: the Environmental Protection Agency, the Department of Interior (including the Forest Service, the Bureau of Land Management, the Geological Survey), NOAA Fisheries, the Fish and Wildlife Service; and the Bureau of Reclamation; at a regional level: the Bonneville Power Authority and the Northwest Power and Conservation Council; at the state level: departments of environmental quality, forestry, agriculture, water resources, and fish and wildlife; at the private level: timber management companies; and numerous more local interests including: tribal nations, locally formed watershed councils, and county governments. For the most part, stream monitoring is not integrated across these entities, even though many measure the same stream biological, chemical, physical, and habitat conditions.

During the past several decades, stream ecosystem monitoring has relied on local site-specific efforts (e.g., the condition above and below point source discharges; the effectiveness of local habitat restoration projects). Compiling status and trend information derived from individual monitoring efforts that were not designed to address regional questions has resulted in summaries of unknown statistical quality. Some evidence points to severe biases in compilations derived from site-specific studies (Paulsen et al. 1998; Peterson et al. 1999). The shifting need for information from local to regional scales has spurred the adaptation of survey design principles developed in other fields (Cochran 1987; Lohr 1999; Thompson 2002) to unique features of stream systems. These unique features include continuous linear networks, changing stream sizes as streams grow from headwaters to downstream termini, and the varying spatial structure of possible stream condition indicators (physical, chemical, biological, geomorphic, riparian).

Stevens and Olsen (2004) reviewed various design approaches that have been developed to survey natural resources. They stated: "Sampling the gamut of natural resources requires a technique that can select a *spatially balanced sample* of finite, linear, and areal resources with *patterned and possibly periodic responses*, using arbitrarily *variable inclusion probability* with *imperfect frame information*, in the presence of *substantial nonresponse*" [emphasis added]. However, none of the current approaches met all their perceived requirements. Building on and integrating the strengths of previous designs, they developed a general approach to designing surveys for natural resources that would meet these requirements, named a generalized random tessellation stratified (GRTS) design. The rationale and design was described by Stevens and Olsen (2004). GRTS spatially balanced designs for points, linear networks, and polygons have been implemented as an R library (R Development Core Team 2004), `spsurvey`, which is available from the Web site *http://www.epa.gov/nheerl/arm*. Instructions for downloading R are available at the above

Web site as is an illustration of the concept applied to stream systems. While developing the GRTS design, Stevens and Olsen (2003) also created a local variance estimator that better expresses the actual precision achieved by the GRTS design when spatial structure is present. The `spsurvey` library includes survey analysis procedures, including the local variance estimator. Two other implementations of spatially balanced designs are available: (1) a Fortran-based application, S-Draw, available at: *http://www.west-inc.com* (McDonald 2004); and (2) a Reversed Randomized Quadrant-Recursive Raster algorithm implemented in a geographic information system (Theobald et al. 2007). Neither includes analysis options.

One of the interesting features of the GRTS design is that it produces an ordered list of one-, two-, or three-dimensional sample points in which each successive point maintains spatial balance and meets the other design requirements. This spatial balance occurs relative to the target resource and can appear spatially unbalanced when plotted, for example, on a statewide map. Regions of a state where the resource is sparse will have fewer points than regions where the resource is abundant. One of the strengths of GRTS and similar designs is that a sample of a specified size can be selected, along with an "over-sample." This capability is especially useful for developing and implementing stream surveys because stream frames (e.g., digital representations of the stream network) are often imperfect, yielding sites that are nontarget. Also, sites are sometimes physically inaccessible or access is denied by landowners. The over-sample works as a buffer because each site rejected in the original sample can be replaced by a site in the over-sample, selected sequentially from the ordered list as needed. With a GRTS sample, this replacement process maintains the spatially balanced random sample of the target population.

In the Pacific Northwest, the usual practice has been to select sites using spatially balanced samples to meet individual monitoring design needs. Because the same design principles are followed, monitoring data can be combined if agencies happen to have overlapping geographic domains and wish to combine their data provided that the same frame, sample elements, and sampling protocols are used (e.g., Larsen et al. 2007). A logical extension is to reverse the usual process and begin by selecting a very large sample, a "master sample" (King 1945; Yates 1981), from which subsamples can be drawn to meet specific needs of particular monitoring programs. As long as the sites that comprise the subsample are drawn in the order they appear in the master list, the subsample meets the important design criterion of spatial balance, as well as randomization.

In this article, we explore the utility of the concept of a master sample through a case study involving selection of a master sample covering the stream/river network in the State of Oregon, U.S.A. The concept is also applicable for designing and implementing surveys of terrestrial and near coastal two-dimensional geographic domains as well, for example, estuaries, wetlands, forests, and rangelands. Many of the same issues that we face in sampling stream networks also arise in these other domains. As we develop the stream network case study, we will also point to applications in other domains. We first describe the properties of this master sample and illustrate its adaptability for several designs. In doing so, we illustrate its potential use to facilitate the integration of monitoring designs across different agencies and across different scales of interest. Then we discuss how this concept might facilitate planning the integration of region-wide monitoring programs across agency responsibilities as well as some of our experiences in implementing the concept in the Pacific Northwest.

2. THE OREGON MASTER SAMPLE

Oregon's stream network is represented digitally, derived from the Geological Survey's 1:100,000 scale hydrographic database (see the National Hydrography Dataset (NHD) at *http://nhd.usgs.gov*). This stream network covers small, headwater streams through large, major rivers. We used this digital representation as the frame from which we selected the master sample. We treat this as a continuous network on which we select a point sample. For purposes of this exercise, we included the full stream/river network, covering both those indicated as perennial and intermittent in the digital files. The network consists of about 82,000 km of perennial streams and about 96,000 km of intermittent streams.

We selected a target master sample size by evaluating the reach length commonly used for field sampling. Stream sampling protocols tend to specify a reach length in the range of 100 to 1,000 m (e.g., to measure stream habitat, or to enumerate fish species or assemblages; Lazorchak et al. 1998; Moore et al. 1999). We used this scale as a guide in selecting a sample size such that points on the frame were on average 1 km apart. It is reasonable that a census could be conducted if the density of points were any greater than one per kilometer. Therefore, a larger sample with points closer together seemed unwarranted. We applied the R-based version of the GRTS site-selection algorithm to generate a statewide ordered list of nearly 180,000 sites. We call this list the Oregon master sample.

2.1 APPLYING THE MASTER SAMPLE

The idea behind applying the master sample is that a sample of a specified size, *n*, can be obtained by selecting the first *n* sites in sequence from the ordered list (or from any start point on the list) for any grouping of the sites. The resultant sample is a spatially balanced random set of sites representing the target resource consistent with the underlying theory supporting GRTS. The master sample can be organized in a variety of ways that allow samples to be selected over different geographic domains, stream types or sizes, or other features by which the frame can be classified. To illustrate this concept, we classified the frame according to a variety of available features. These include an approximation of stream size: Strahler stream order by which small first-order streams merge to form second-order streams; second-order streams merge to form third-order streams, etc. (Strahler et al. 1987); flow status (continuously flowing perennial streams; streams with intermittent flow, usually the smaller streams), the Geological Survey's hydrologic accounting unit (HU; Seaber et al. 1987; Legleiter 2001; see Table 1), Oregon Department of Environmental Quality's candidate reporting regions (OR DEQ 2005), and general land ownership (e.g., federal, state, tribal, private). We note that many of these and other geographic classification variables could be used in applications of the master sample concept to terrestrial systems (e.g., forest condition by ownership). Example features are summarized in Table 1.

Table 1. A list of candidate classification variables used to organize the master sample.

Site identifier	Ecoregion[2]
Location (Lat/Long)	Level 2
Flow status	Level 3
Hydrologic Unit[1]	Level 4
4th field code	Reporting regions
5th field code	Oregon Dept. of Env Quality
6th field code	Land ownership
Strahler stream order	Other geo-referenced attributes
Elevation	

[1] The U.S. Geological Survey developed a system to account for water resources in the United States (Seaber et al. 1987; Legleiter 2001). This system divides the country hierarchically, essentially by watersheds, starting with the largest basins (Columbia, Mississippi, Missouri, etc.), then subdividing these. This basic accounting system covers four levels, each level distinguished by a two-digit code; the USGS finest level is a "4th field" with an 8-digit code. Others have taken the process further, creating 5th and 6th field levels with corresponding 10- and 12- digit codes.

[2] The concept of an "ecoregion" reflects the notion that identifiable ecosystem spatial patterns occur and can be delineated as maps, e.g., mountains, plains, deserts. Omernik (1987, 2004) and Bailey (1995) describe ways of defining and delineating ecoregions. We use Omernik's system; it contains four levels, from coarse scale ecoregions (level 1) to fine scale ecoregions (level 4).

These classification variables, along with unique site identifier, site location, and some design attributes, make up the master sample file. Classification features not in the master sample file can be added by associating them with each site. The general principle is that a sample can be selected by first classifying the ordered sample into the Forest), then picking the *n* sites from the ordered list (in order) to achieve the desired sample size.

2.2 OREGON MASTER SAMPLE EXAMPLES

Assume that the Oregon master sample has been adopted as basis for coordinating monitoring programs across agencies and that an agency or consortium of agencies has been identified to oversee its "distribution" and implementation. We created a series of examples to illustrate various ways that specified samples can be drawn from the master sample, moving from some very simple situations to more complex.

Example 1: Statewide study of Oregon perennial streams based on 250 sites. Solution: (1) classify the master sample into perennial and nonperennial streams, and (2) select the first 250 sites in the perennial group.

Example 2: Statewide study of Oregon perennial streams reported by five Oregon Department of Environmental Quality's candidate reporting regions (OR DEQ 2005) and ensuring the samples balance approximately equally among headwater (Strahler first-order), wadeable (Strahler second- and third-order), and nonwadeable (Strahler fourth- and higher order) streams. Sample size is 50 for each reporting region for a total of 250 sites. Solution: (1) Sort the master sample into the reporting regions, then by perennial/nonperennial, then by stream order. (2) Determine the number of sites in each stream order category for

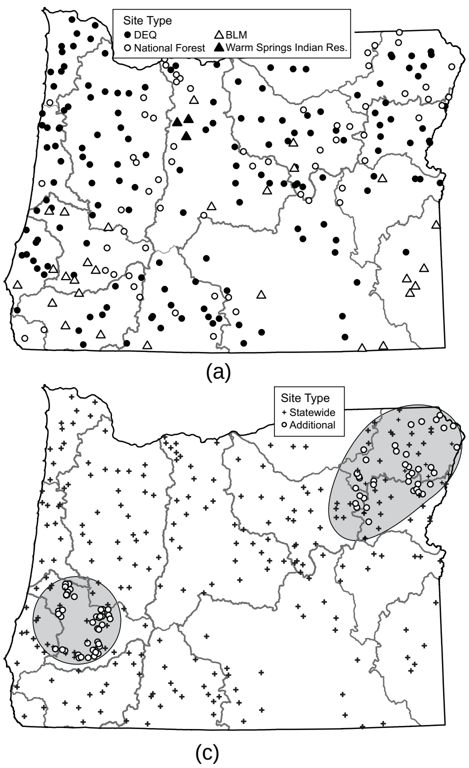

Figure 1. Examples of the spatial distribution of sample points selected from the Oregon master sample. Figure 1(a) illustrates a statewide sample with an equal number of sites in each of Oregon Department of Environmental Quality's five reporting regions (reporting regions are outlined by heavier lines); sites are coded by "agency ownership." Figure 1(b) illustrates additional sites (open circles) allocated to each of three subbasins (shaded) within three of five reporting regions. Figure 1(c) illustrates additional sites (open circles) allocated to a national forest (shaded) and to a Bureau of Land Management district (shaded). Figure 1(d) illustrates additional sites (open circles) allocated to small watersheds (shaded).

each reporting region, as follows: (total number of sites desired in each region)/(number of stream order categories) = 50/3 = 17 (rounded up). (3) For each of the stream order groups within each reporting region, select the first $n = 17$ sites. The design is illustrated in Figure 1(a). The selected sites in Figure 1(a) are coded by "agency ownership" to suggest that, for a statewide monitoring program, each of these agencies could implement the monitoring at the sites within their management purview, tied together with the common design.

Example 3: The same agency subsequently adds special studies with 50 sites allocated to each of three "subbasins" allocated among the stream sizes as indicated in Example 2. Solution: (1) Follow steps 1–3 as in Example 2. (2) For the three subbasins in which a larger sample size is desired, continue down the ordered list within each of those subbasins for each stream category until $n = 17$ within each nested group. Note that some of the sites in each group would have already been selected in Example 2. Proceeding down the ordered list provides the additional sites needed to meet the target sample size for that subpopulation (Figure 1(b)).

Example 4: The Forest Service and the Bureau of Land Management (BLM), both of which manage large tracts of land (and the streams that traverse these lands) in the western U.S., initiate studies in one of the national forests and in one of the BLM districts with a sample size of 50 in each. Solution: (1) Follow steps 1–3 of Example 2. (2) For the selected national forest and BLM district in which a larger sample size is desired, continue down the ordered list by stream order within those groups until $n = 17$ within each nested group. Note that some of the sites in each group would have already been selected in Example 2. Proceeding down the ordered list provides the additional sites needed to meet the target sample size for that subpopulation (Figure 1(c)).

Example 5: An agency designs a monitoring program that first selects a subset of small watersheds statewide and then stream sites within each selected watershed (see Gallo et al. 2005). Solution: (1) Use GRTS to select a statewide sample of 50 USGS sixth field HUs. (2) Then select six sites in each HU from the part of the master sample that fell in each HU. This two-stage design first produces a spatially balanced set of HUs across the state. Then, following the process in Examples 2–4, sites are selected within each chosen HU, two sites from each of the stream size classes. Note that one or more of these sites might have already been selected in the statewide sample (Figure 1(d)).

Given that the master sample is an equal inclusion density survey design, the appropriate inclusion densities for each design can be calculated knowing the stream length and number of sites selected within each category used to allocate the sites in the design, for example, by OR DEQ region—Strahler group, by land ownership—Strahler group.

2.3 ADDING CLASSIFICATION VARIABLES

The master sample framework has flexibility with respect to adding classification variables. The current version of the Oregon master sample includes a variety of classification variables selected primarily for illustrative purposes (Table 1). However, this is not a complete list of possible classification variables that might be desired for allocating sampling effort. Grouping sites by variables not included in the master sample can be accommodated in several ways. One way is to classify the master sample in its entirety by the new classification variables, associating each site on the master list with its respective additional class. An efficient method would be to intersect the point locations of each site with a digital map depicting the spatial pattern of the classes of the new variable. This would expand the master file with the additional variable (or variables if more than one classification variable were to be added). For example, one might want to incorporate elevation as a variable (e.g., elevation bands), or counties. The addition of classification variables need not be statewide if the domain of interest covers only a part of the state. For example, a single watershed might be targeted for monitoring, for which some important classification variable is not in the current master file. Only the part of the master sample in that watershed would be classified with the appropriate digital map representing the classes of interest.

2.4 INCLUSION DENSITIES AND SITE WEIGHTS

The randomization incorporated into GRTS allows each point in the stream domain of interest to be selected with a known probability of being included in the sample (inclusion density, or its inverse, sample weight). The sample weight specifies the stream length represented by each point; smaller samples yield larger weights because each site represents a greater part of the stream network. If digital stream networks are used as the frame for sample selection, weights can be determined by dividing the domain's length by the number of samples. This process can be relatively straightforward for simple designs, but can become an accounting challenge for more some complex designs. In Example 1, the site weights, 164 km, are equal because the selection process did not differentially allocate sites to different groups. In the second example, in which the sample size was set by reporting region and stream order, weights for sites in each reporting region/stream size are calculated by dividing the stream length in the group by the number of sites in that group. The challenge for complex designs is to clearly describe each of the unique groups, determine the stream length and sample size in each of the groups, and then calculate the weights. Obviously, one result of designs with multiple groups used for site allocation is that weights differ across the multiple groups. Note that both the master sample sites used and the sample frame must be classified by the groups.

3. UTILITY OF A MASTER SAMPLE

An ambitious vision is for a master sample to serve as an integrating design framework around which stream monitoring by multiple agencies can be coordinated. One aim is reduce duplication of field sampling effort by having one agency use data collected at common sites by another agency. Another is to increase sample size to make estimates of status or trend by combining multiple studies. At present, coordinated monitoring is difficult for a variety of reasons. One significant reason is the lack of common protocols for measuring attributes of interest, although agencies are addressing the issue. Another reason is that monitoring programs may select sites by targeting individual streams or small stream networks without considering them in the context of a larger population of streams. As a result, combining data derived from these produces summaries with unknown biases and such programs are not considered further. Although we recognize these reasons, we are aware of multiple studies occurring in the northwest that can be combined, leading us to consider use of a master sample as a means to coordinate monitoring.

When multiple monitoring programs use the same master sample, then the programs will have some sites in common if their target populations overlap. Unless a monitoring program requires field measurements in addition to those collected by a program that has already visited the common sites, existing data can be used—a substantial cost savings. Even when additional measurements are needed, savings can still be significant.

Having the same master sample used to select sites by multiple agencies enables the combined set of sites to be viewed as coming from a single design with multiple objectives. The design is an unequal probability design where the unequal probability categories reflect the multiple objectives of the agencies. It is the design that would have been implemented if all the agencies had agreed to design and conduct their monitoring at the same time. Although desirable, agencies typically do not know their monitoring requirements at the same time, making it impossible to do a single combined design.

An alternative to a master sample is for each monitoring program to develop independent survey designs. Theoretically it is possible to combine the surveys in a statistically sound manner. However, unique decisions in designing the individual programs can make this difficult. A significant challenge can be determining the appropriate inclusion densities, or weights, for the combined survey. Each survey's sample frame must be acquired, differences identified and a combined frame developed. A master sample has a single sample frame that is the basis for combining the surveys. It may be necessary to add additional variables to the sample frame to incorporate criteria used to subset the sites for each study, a much simpler task. Once this is done, calculating the inclusion densities for the combined studies is straightforward.

Independent survey designs, when combined, are not likely to result in a combined design with the same spatial-balance properties compared to what would have occurred if they had been done as a single design, even if each were a spatially balanced design. For example, in a region that is common between two surveys, doing a single spatially balanced design results in better spatial-balance than doing two independent spatially balanced designs.

Using a master sample to coordinate monitoring across agencies has many obvious benefits, particularly with respect to overcoming the challenges associated with individual agencies creating independent monitoring programs. The agency responsible for reporting on the condition of streams across the state would have ready access to the increased sample size derived from the intensified monitoring in some areas of the state. Multiple agencies participating collaboratively would reduce redundancies in monitoring efforts that currently occur as agencies proceed independently. Individual agencies could make use of data already being collected for broader regional purposes. The net effect of the integrated sample design would be a more efficient allocation of sampling sites to achieve varying purposes and maintain desired statistical survey design principles. This framework could also provide additional motivation toward adopting common protocols for core attributes that tend to be of interest to most agencies that monitor stream networks without restricting any agency's need to include unique indicators. In addition, the requirement for easy data sharing would stimulate the development of a common data storage-retrieval system easily accessible to all participants.

4. IMPLEMENTATION

Creating a master sample and illustrating its potential use is straightforward. Actual implementation across multiple agencies intending to monitor the same natural resource, but with partially differing objectives or legislative mandates, domains of interest, monitoring histories (e.g., legacy monitoring programs that cannot be dropped) and partially overlapping indicators presents real challenges. The major challenges are organizational and political. These challenges are being explored by agencies monitoring stream systems in the northwestern U.S.

One key to using a master sample to coordinate monitoring across agencies is quick access to information on use of the master sample by other agencies and to resulting monitoring data. In addition to making the master sample available, others must have access to (1) the sample frame used to generate the master sample, (2) a site evaluation file integrating information about the sites used in all studies, (3) metadata describing each study, (4) any digital geographic data used to define study regions or add new characteristics to the master file and sample frame, and (5) actual monitoring data. We summarize the status of one implementation set up by the State of Washington's Department of Ecology (WA DOE).

As part of Washington's development of a Comprehensive Monitoring Strategy to evaluate its "Watershed Health and Salmon Recovery Efforts," WA DOE was charged to develop a statewide probability-based sampling effort "to inform on the condition of streams, and rivers" (*http://www.ecy.wa.gov/programs/eap/stsmf/*). WA DOE's intent is to be able to describe the status and trends in stream/river habitat and water quality at three spatial scales: Statewide, by Salmon Recovery Region (SRR), and by Water Resource Inventory Area (WRIA). WA divided the state's water resources into SSRs to facilitate the management of threatened and endangered salmonid species. It also divided the state's water resources into WRIAs, as a reasonable size at which the state's water resources (stream habitat and water quality) could be managed by the combination of federal, state, and local management agencies. Nine SSRs, and one region that is not designated as an SSR, along with 62 WRIAs comprise the state's stream systems; maps are available on the above Web site. WRIAs are generally hierarchically embedded in SSRs.

After several workshops and numerous discussions, WA DOE adopted the master sample concept as an appropriate design framework to meet their needs to facilitate stream sampling by a variety of agencies and allow for development of sound statistical summaries. WA's Department of Natural Resources provided us with a digital representation of their target statewide stream resource, on which we selected a master sample with distances between sample points on average 1 km. WA had decided to use a statewide 1:24,000 digital representation of their stream networks, with significantly more small streams represented than on the NHD+ 1:100,000 versions. As a result, this master sample file consists of approximately 480,000 points, along with many of the same attributes as in the Oregon master sample used in the illustration above.

WA DOE posted this master sample on their Status and Trends Web site: *http://www.ecy.wa.gov/programs/eap/stsmf/*, but restricted to sites on nonfederal lands. On that Web site, the master sample is described, organized by first by SSR, then by WRIA within SSR, with three files per WRIA. One is a list of the sites comprising the master sample (an MS-EXCEL spreadsheet); a second is a table summarizing the number of sites by WRIA and stream order within each SSR, and the third is guidance on evaluating the sites that an agency might select to visit. This site evaluation guide is critical as it provides information about the status of a site with respect to whether it is a target (the digital representation is imperfect and there are errors), whether a candidate site was sampled and if not, why not (often selected sites cannot be sampled because access to the site might be denied by adjacent landowners, or the site is too dangerous to reach). The actual list of visited sites is used to determine the site inclusion densities. WA DOE explicitly states that (as of this writing) it does not have funds to support the Web site. We consider this Web site a prototype work in progress.

The potential for a Web-based system by which a master sample is implemented and managed is clearly an attractive avenue to explore; technological advances in Web design and capability likely support the needed functions. Central would be the master sample itself, a sample file containing at least the list of sites coded by a unique identifier for each site, along with a range of site attributes including geographic location, design information, classification variables (of the type indicated in Table 1), and evaluation status (initially set to "not evaluated"). Complementary Web pages would include guidance on selecting sites from the master list to meet an individual agency's objectives, documenting the design and status of sites selected (e.g., target/nontarget, sampled/not sampled; if not sampled, why not). Additional capabilities could include: (a) interactive functions by which an agency submits its design and set of sites selected, evaluated, and sampled (along with a portal allowing access to data collected); (b) a mechanism by which the classification variables could be expanded and the master list coded to reflect these additions; (c) a process to incorporate frame improvements How many of these capabilities could be built into the website and run with minimal involvement of human oversight remains an area open for exploration.

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