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Cost-Effective Sampling of Ground Water Monitoring Wells

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COST-EFFECTIVE SAMPLING OF GROUNDWATER MONITORING WELLS

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INTRODUCTION

Cost-Effective Sampling (CES) is a method for estimating the lowest-frequency (and, as a result, lowest-cost) sampling schedule for a given groundwater monitoring location which will still provide needed information for regulatory and remedial decision-making. Its initial development was motivated by the preponderance of sampling results showing little changes over time or falling below detection limits at Lawrence Livermore National Laboratory's (LLNL's) environmental restoration sites. The fact that many locations had never shown, or had ceased for some time to show, any detectable levels or changes in levels of contamination suggested that some of their 700+ groundwater monitoring wells were being sampled more often than necessary. Similar concerns were raised at the Savannah River Site (SRS), where some 10,000 samples are taken per year from 1500+ monitoring wells. The question facing both organizations has been how to reduce sampling costs while still satisfying both regulatory agencies and their own scientists and engineers that sufficient data will be collected for decision-making purposes.

The first version of CES was implemented at LLNL's Livermore site in 1992 and approved by regulators under CERCLA. It is designed to statistically evaluate the sampling results to be able to recommend sampling schedules of groundwater monitoring locations for a common suite of volatile organic compounds, with the goal of reducing frequencies. The table below presents the sampling status of monitoring wells at LLNL's two restoration sites both before and after the application of CES.

LLNL Site		Sampling Schedule		
		Quarterly	Semi-annual	Annual
Main	Before CES	212	77	7
	After CES	81	65	150
S300	Before CES	297	0	26
	After CES	180	117	134

It is estimated that these reductions in frequency have saved $390,000 annually in labor, data management, and laboratory costs. The remainder of this paper describes the basic ideas on which CES is based and presents the decision-logic for the version that has been in use at LLNL. Enhancements and future directions stemming from the joint LLNL/SRS project are discussed in the section on DIRECTIONS.

FOUNDATIONS OF CES

The original method for determining sampling frequencies at LLNL used the well location with respect to the contaminant plume (near or within a plume) as the deciding factor for the sampling schedule (see Figure 1). This decision process caused the majority of the wells to be sampled quarterly, even those that had shown little or no change over an eight year period. The major problem with this method was that it did not account for the slow rate of migration of the contaminants on the site. Because of this slow rate of migration, the concentrations within a well have tended to remain relatively constant.

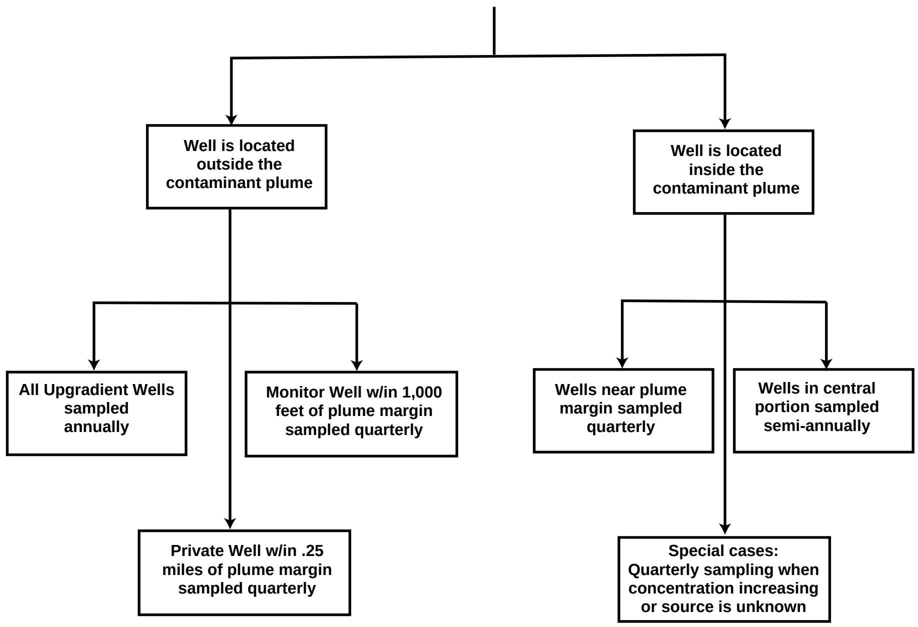

Figure 1. Original Method of Setting Sampling Frequencies.

This intra-well consistency brought about the idea of basing the sampling frequency on the changes in concentration seen at a specific well, rather than just the well's location with respect to the plume. CES recommends sampling frequencies based on quantitative analyses of the trends in and variability of important contaminants at a given monitoring location. It then interprets this information by means of decision trees to arrive at a recommended sampling frequency. An essential aspect of the system is its ease of interpretation. The goal has been to keep to widely-understood statistics that fit into decision-logic familiar to people involved with environmental chemistry.

In the version of CES currently in use at LLNL, the determination of sampling frequency for a given location is based on trend, variability, and magnitude statistics describing the contaminants at that location. The underlying principle is that a location's schedule should be primarily determined by the rate of change in concentrations that have been observed there in the recent past. The higher the rate of change, whether upward or downward, the greater the need for frequent sampling. Conversely, where little change is observed, a more relaxed schedule can be followed.

A second rationale for more frequent sampling is the degree of uncertainty displayed in the measured concentrations. Low overall rates of change can be offset by a higher degree of variability, requiring that a more frequent schedule be maintained to better define the likely degree of contamination at that location.

Finally, the magnitude of the measured concentrations affects the interpretation that is placed on rates of change. Clearly, a yearly change of 50 parts per billion (ppb) means something quite different when the median concentration is 10 vs. 1000 ppb.

DECISION-LOGIC

A few issues must be clarified before proceeding to a discussion of the logic contained in the flow charts in Figures 2, 3, and 5. The first of these involves the available scheduling options. In the future, it is expected that fairly precise estimates of needed frequency, down to a resolution of weeks, will be made. This precision will become important when scheduling to assess the effects of remedial actions is incorporated into the system. For the time being, however, only compliance monitoring is being addressed. So, the scheduling options have been restricted to a multiple of the traditional quarterly sample: Quarterly, Semi-annual, and Annual.

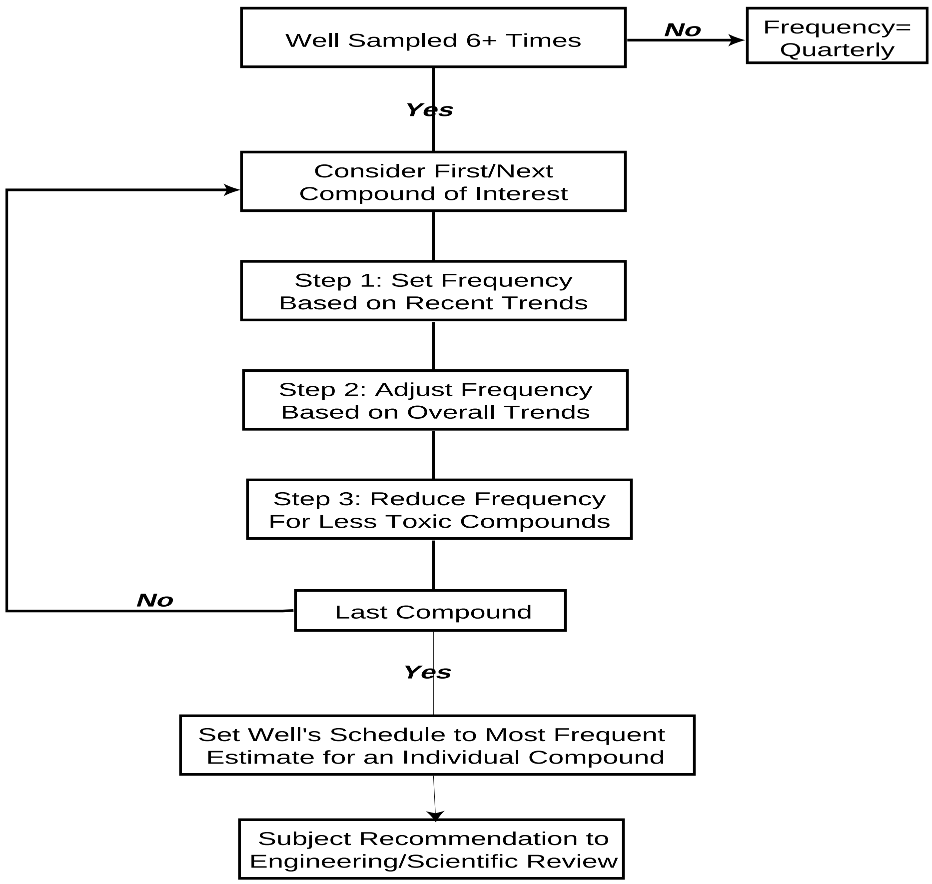

Figure 2. Overview of Steps in Cost-Effective Sampling.

Second, each scheduling category has been associated with a base rate of change. The Annual category is reserved for trends of less than 10 parts per billion (ppb) per year. The Semi-annual category falls in the range of 10 - 30 ppb per year. The Quarterly category is associated with rates of change in excess of 30 ppb per year. However, high and low degrees of variability can move a particular location out of the Semi-annual and into the Quarterly or Annual categories. The currently used cut-offs have been tailored to 11 VOCs of particular interest at LLNL (carbon tetrachloride; chloroform; 1,1-DCA; 1,2-DCA; 1,1-DCE; 1,2-DCE; Freon 113; PCE; 1,1,1-TCA;

TCE; and Freon 11) and to the relatively low rates of change that are often seen at arid sites. In future versions, a more generally applicable scheme for setting cut-offs will be employed.

Overview

The overall flow of CES is shown in Figure 2. To be eligible for consideration, a location (usually a groundwater monitoring well or piezometer) must have already been sampled on at least six occasions, which is roughly equivalent to 18 months of quarterly sampling. Newly installed wells must be sampled frequently to build up a history for the purposes of analysis. The decision-rules of the system are applied independently to each contaminant in the target list for a particular location. The schedule assigned to the location is the most frequent schedule estimated for any individual contaminant.

The evaluation of each contaminant proceeds in three steps. First, an initial estimate of the desirable schedule is obtained by analyzing the most recent trend and variability information. In step 2, the recent trend is compared with the overall or long-term trend to identify cases where the step 1 decision should be overridden by an estimate based on overall statistics. In step 3, a correction is made for the less toxic substances on the list. Even though their yearly rates of change may be relatively high, their estimates are revised downward so long as the magnitude of the concentrations involved fall below certain limits. Finally, all CES recommendations are subject to change as a result of scientific and engineering review. Common reasons for overriding a recommendation are anticipation of future remedial actions and public relations considerations pertaining to off-site locations.

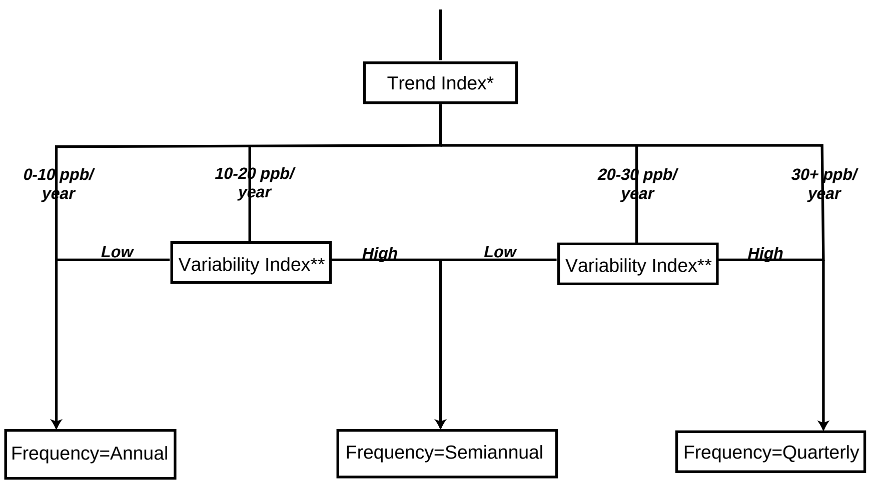

Figure 3. CES Step 1 Decision-Logic.

Step 1: Set Frequency Based on Recent Trends

As was mentioned earlier, the primary focus of CES is on trends or rates of change. This is currently defined as the least-squares slope obtained by regressing time against measured concentrations. The advantage of this statistic is its ease of interpretation. The slope can be expressed as a yearly change in concentration. Its disadvantage is that its suitability for use with non-normal data is questionable. Part of this problem could be solved by linearizing the data by a means of a natural log transformation. However, this introduces interpretation problems which, for this first simple verion of CES, we are trying to avoid.

Rate rather than direction of change is the dominant factor. All rate and rate-related statistics use absolute values. Based on the rate of change information, a location is routed along one of four paths (see Figure 3). The lowest rate, 0-10 ppb per year, always leads to an annual frequency schedule. The highest rate, 30+ ppb per year, always leads to a quarterly schedule. Rates of change in between these two extremes are qualified by variability information, with higher variability leading to a higher sampling frequency. Figure 4 illustrates an annual recommendation for TCE generated at this step due to a low rate of change, despite the fact that concentration levels are well above drinking water standards.

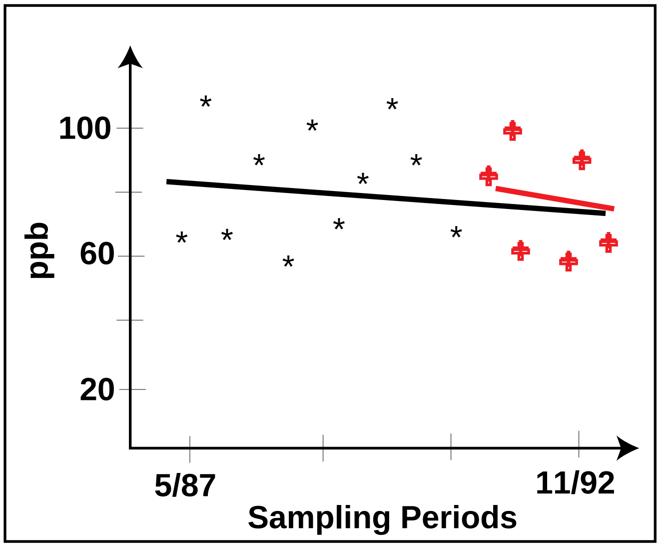

Figure 4. Annual Recommendation Generated by Step 1 Logic. (+'s indicate data from recent samples.)

Variability is characterized by a distribution-free version of the coeficient of variation: the range divided by the median concentration. This statistic corrects for the influence of magnitude on variability, which is an important consideration given that the range of concentrations in VOCs routinely vary over three orders of magnitude. The cut-off of 1.0 distinguishing high vs. low variability was derived empirically from the data distributions. It is the median value of that statistic calculated for the two most active contaminants at LLNL, TCE and PCE, across all locations in a benchmark dataset. Both the trend and variability statistics in Step 1 are calculated from the 6 most recent sampling periods worth of data.

Step 2: Adjust Frequency Based on Overall Trends

While emphasis is placed on setting frequencies from recent data, there are cases where a long-term history of change may override the Step 1 decision. The first three boxes in the Step 2 flow chart (see Figure 5) weed out cases where such a re-evaluation is undesirable or trivial. The goal is to examine only those cases where the overall rate of change is significantly greater than the recent rate of change.

The major branch in Step 2 is meant to distinguish two ways in which the overall trend may be significantly greater than the recent trend. The right-hand side considers the majority of cases. The overall trend is definitely but not extremely greater than the recent trend: so the sampling frequency is re-estimated using Step 1 logic but with overall rather than recent statistics. An example of this case is given in Figure 6, where the flat recent trend, which produced an Annual recommendation in Step 1, was upgraded to Semi-annual in Step 2 when the overall statistics were considered.

The left-hand side considers the situation where the recent trend is very flat relative to the overall trend. Two such cases are shown in Figure 7. 7(b) shows concentrations dropping and leveling off at a low level of magnitude, as might be expected if a slug of contaminant had passed by the monitoring location. In this case, current thinking is that the (probably) Annual decision made in Step 1 is still appropriate. 7(a), in contrast, illustrates the case of rising concentrations which are then leveling off. Here, there is as yet no general conclusion as to the best course of action. So, the sampling frequency decision is left entirely to scientific/engineering judgment.

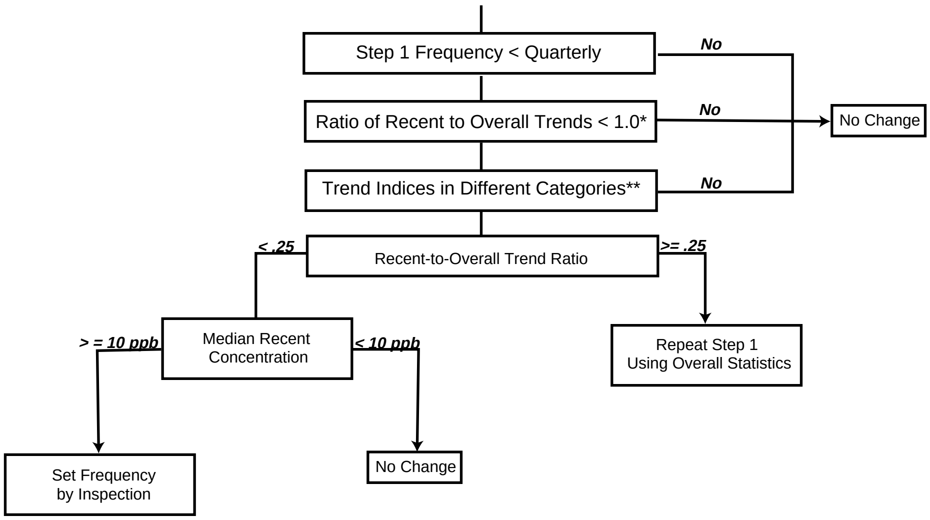

Figure 5. CES Step 2 Decision-Logic.

<u>Step 3: Reduce Frequency for Less Toxic Compounds</u>

Not all compounds in the target list are equally harmful. Because of differences in drinking water standards, an average trend of 25 ppb/year for TCE is considered more serious than the same trend for Chloroform or the two forms of Freon. So, quarterly and semiannual decisions are reduced one level if the maximum concentration in the recent set of samples is less than 1/2 of the compound's MCL. It is expected that future versions of CES will tailor all explicit cut-offs in the flow-logic to individual contaminants.

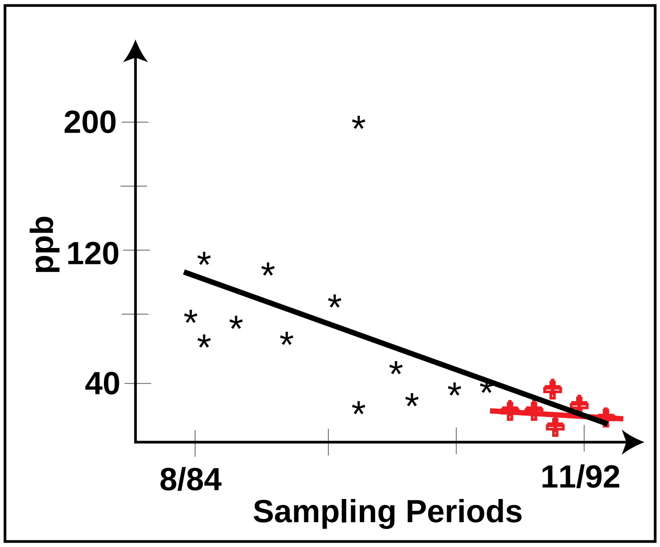

Figure 6. Annual Recommendation from Step 1 Increased to Semi-annual in Step 2. (+'s indicate data from recent samples.)

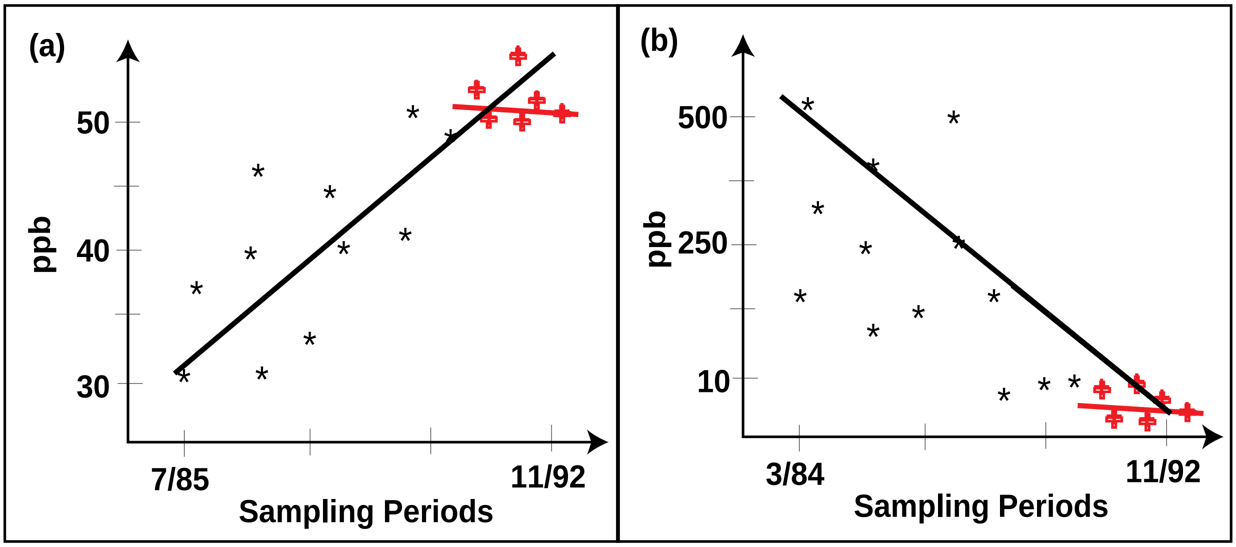

Figure 7. Step 2 Examples of Leveling-Off. (a) After a Steep Rise. (b) After a Steep Drop. (+'s indicate data from recent samples.)

DIRECTIONS

While technical staff at LLNL's Environmental Restoration Division have been focusing on the interpretation of data patterns, statisticians at the Savannah River Technology Center have explored more rigorous statistical approaches to the problem of groundwater sampling frequency estimation. A limited amount of statistical guidance is available for sites wishing to reduce their sampling schedules in a non-arbitrary manner. EPA documents written for RCRA facilities (U.S. EPA, 1989; U.S. EPA, 1992) suggest using techniques such as Darcy's Equation to estimate the time between independent samples of groundwater based on the physics of flow. A second EPA publication presents a method for estimating sampling intervals from a combination of a first-order autoregressive model of groundwater time series data and the standard error of that series (Barcelona et al., 1989). A third, and especially interesting, approach is the creation of temporal variograms to estimate time correlations among samples in the same way that spatial variograms are used to estimate spatial correlations (Oswina et al., 1992; Tuckfield, 1994). All the above approaches are geared toward determining the time-interval at which statistical independence is achieved. This is a key assumption to the proper application of standard significance tests and also provides a logical foundation on which to base sampling frequencies. However, these more purely statistical approaches to the sampling frequency problem have more difficulty gaining acceptance because of the highly specialized knowledge required to properly implement them. The goal of the joint venture between Livermore and Savannah River is to blend the practical, qualitative aspects of the version of CES described in this paper with the more rigorous statistical foundations of the methods being examined at SRS.

The current version of CES is oriented toward compliance monitoring. That is, it is assumed that only natural processes are affecting the levels of measured concentrations. Increases in frequency dictated by remedial actions are left to the judgment of personnel reviewing the recommendations. To become more applicable throughout the life-cycle of a groundwater project, there are several improvements that should be made. First, the current version is oriented toward reducing schedules and does not contain logic for increasing previously-reduced schedules or estimating schedules on a finer grain than quarterly. Issues that need to be addressed include the statistical interpretation of data that is being collected over long and irregularly-spaced time frames, expanding the compounds to which the logic applies, and providing a firmer foundation for the selection of cut-off points. Second, new functions which need to be added include: 1) chemical signature analysis to identify minimum suites of contaminants for a well, 2) a simple flow and transport model so that schedules of downgradient wells are increased in anticipation of movement of contamination in their direction, and 3) a sampling cost estimation capability so that the impact of schedule reductions can be quickly assessed.

By blending the qualitative and quantitative approaches to the determination of sample frequencies, the joint project hopes to create a system which rests on a technically defensible foundation while retaining the qualities of ease of interpretation and relevance to the decision-making context in which its is being used.

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