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Cost-Effective Sampling of Ground Water Monitoring Wells

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INTRODUCTION

Cost-Effective Sampling (CES) is a systematic methodology for estimating the lowest-frequency sampling schedule for a given groundwater monitoring location which will still provide needed information for regulatory and remedial decision-making. Its initial development at Lawrence Livermore National Laboratory (LLNL) was motivated by our desire to have a systematic argument to reduce sampling frequency in wells where there is little change in contaminant concentrations over time and/or where the preponderance of sampling results fall below detection limits. The fact that many locations had not shown, or had ceased for some time to show, any detectable levels of contamination suggested that some of our 700+ groundwater monitoring wells were being sampled more often than necessary. We implemented our initial version of the methodology at LLNL in 1992 with local regulatory agency approval.

Similar concerns were raised at the Savannah River Site (SRS), where some 10,000 samples are taken per year from over 1500+ monitoring wells. The total price-tag for these SRS sampling activities includes not only an estimated $10,000,000/year in laboratory analytical fees but also hidden costs associated with such activities as waste-water disposal and data management. 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.

LOCATIONAL VS. DATA-ORIENTED SAMPLING RATIONALES

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 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 the slow migration, concentrations within a well have tended to remain constant.

This intra-well consistency brought about the idea of basing the sampling frequency on the changes in concentration seen at a given well, rather than that well's location with respect to the plume. Scientific and engineering review of the CES sampling frequency recommendations ensures that considerations of location with respect to the contaminant plume and remediation or other activities underway are not overlooked. 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 desired sampling frequency. An essential aspect of the system is its ease of interpretation. The system uses appropriate, widely-understood statistics that fit into decision-logic familiar to people involved with environmental chemistry.

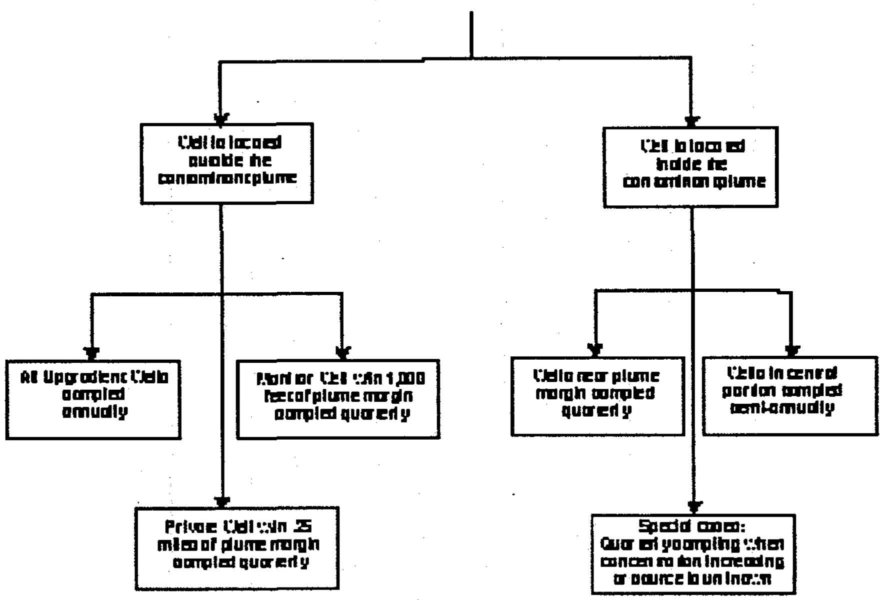

Figure 1. Location-Oriented Method of Setting Sampling Frequencies.

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 recommended.

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. On the other hand, a high rate of change that is highly predictable warrants a lower sampling frequency.

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. The significance of the absolute concentrations also varies by compound. The hazard associated with a 300 ppb concentration of TCE is interpreted differently from a 300 ppb concentration of Chloroform.

DECISION LOGIC CHARTS - IMPLEMENTED VERSION

As was mentioned in the introduction, early versions of CES have been implemented, with regulatory approval, at LLNL since 1992. As a result, specific aspects of the decision logic are in the process of being re-evaluated. To avoid confusion, only the currently implemented version of the decision logic will be described here. Results of applying both the implemented and experimental versions are presented in the section on COST-SAVINGS.

A few issues must be clarified before proceeding to a discussion of the logic contained in the flow charts in Figures 2, 3, and 4. 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 sampling: quarterly, semi-annual, and annual.

Second, each scheduling category has been associated with a base rate of change. The annual category is reserved for trends of less than 10 ppb per year. The quarterly category is associated with rates of change in excess of 30 ppb per year. The semi-annual category falls in the range of 10 - 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 the version under development, a more generally applicable scheme for setting cut-offs is being employed.

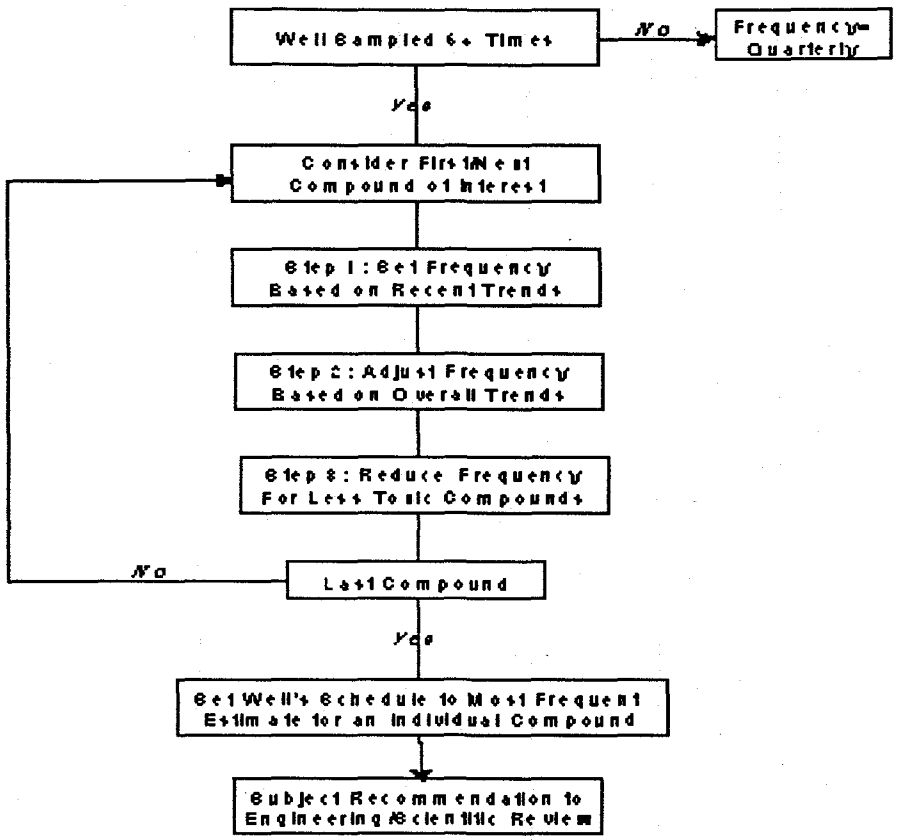

Figure 2. Overview of Steps in CES - Implemented Version

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. This includes newly installed wells. 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 recommendations are the desire to monitor for changes due to on-going or future remedial actions, and public relations considerations pertaining to off-site locations.

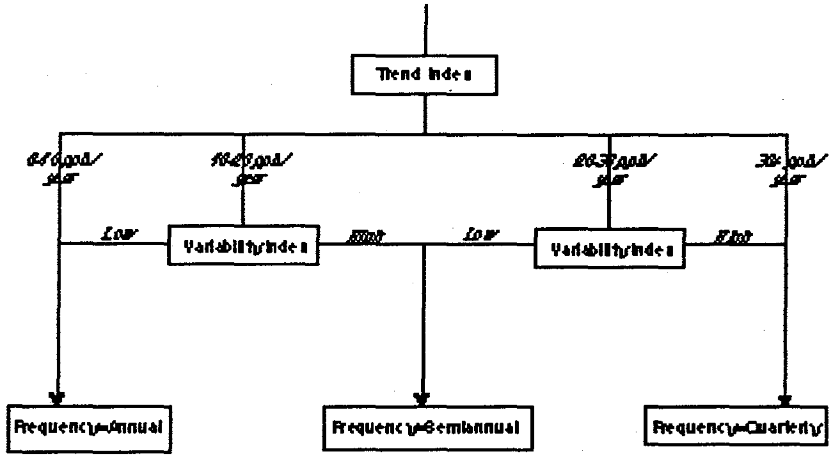

Figure 3. Step 1 Decision Logic - Implemented Version

Step 1: 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 means of a natural log transformation. However, this introduces interpretation problems which, for this first simple version 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.

Variability is characterized by a distribution-free version of the coefficient 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 varies 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 data set. Both the trend and variability statistics in Step 1 are calculated from the 6 most recent sampling periods worth of data.

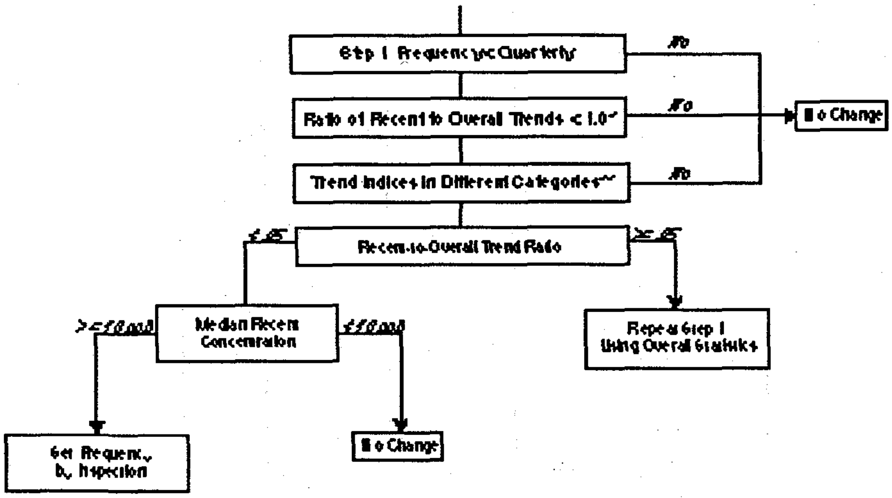

Figure 4. Step 2 of CES - Implemented Version

Step 2. 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 4) 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.

The left-hand side considers the situation where the recent trend is very flat relative to the overall trend. If the flattening occurs at a low level of concentration, the Step 1 decision is retained. If not, the decision is left to scientific/engineering judgment.

Step 3. 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 far more serious than the same trend for Chloroform or the two forms of Freon. So, quarterly and semi-annual 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.

COST SAVINGS—IMPLEMENTED AND EXPERIMENTAL VERSIONS

The table below presents the sampling status of monitoring wells at LLNL's main restoration site both before and after the initial application of CES (1992).

	Sampling Schedule

	Quarterly	Semi-annual	Annual
Before CES	212	77	7
After CES	81	65	150

It is estimated that this 40% reduction in the number of samples taken at the main site have saved $230,000 annually in labor, data management, and analysis costs.

SUMMARY

The temporal and spatial sampling methodologies currently being implemented and/or developed are 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 ground water cleanup project or for compliance monitoring, several improvements are envisioned, including 1) chemical signature analysis to identify minimum suites of contaminants for a well, 2) a simple flow and transport model so that sampling 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 sampling plans, we hope 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 it is being used.

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