Aquatic Sediment Sampling and Analyses*

Richard B. Shepard, Ph.D.†

March 16, 2011

Introduction

Collecting sediment samples for analysis of contaminants—particularly in river systems—is not just a matter of going out with a bucket and shovel. In fact, it is much more complex than a water quality survey, aquatic biota survey, or any terrestrial sampling program. Monitoring of sediment contaminants frequently is done to determine whether the sediments are a sink or a source of the chemicals of interest, and to evaluate the effects of the contaminants on the aquatic ecosystem as a whole.

When contaminated sediments may be present there is the potential for very expensive liability payments by bank-side industries, so the sampling program must be absolutely of the highest caliber; that is, it must be technically sound and legally defensible. The costs of laboratory analyses can far exceed the costs of collection of materials to be analyzed[1]. This means that costs can greatly exceed budgets if sediments must be collected and analyzed again because the original samples were collected at inappropriate locations or did not adequately represent the area of interest. Other factors that influence the cost of the study include the selection and use of sediment sampling equipment, sample handling, storage, and transport to the analytical laboratory.

Terrestrial soil sampling is less complicated because soils are stable (except during erosion by water or wind). The spatial and statistical analyses applied to aquatic sediments can be applied with equal validity to terrestrial soil samples.

---

†President, Applied Ecosystem Services, Inc., Troutdale, OR

[1] In a study of sediment contamination in the lower Columbia River, the laboratory had to boil the sands and gravels in concentrated nitric and hydrochloric acids in order to remove the inorganic materials so they could be measured. In such cases, toxic materials may be present but are not biologically available.

Sampling Program Design

To maximize the return on investment in a sediment characterization program, about 60 percent of the scheduled time should be devoted to detailed planning. Both where and how samples are collected affect the quality of the results. Such sampling decisions should be based on the objectives of the sampling program.

Program Objectives

Applied sampling programs to examine contaminant distributions, concentrations, dynamics, and ecosystem effects must be based on a solid foundation of sediment dynamics in the study area. If there are no data that describe the spatial distribution of sediment particle sizes, their movements, and the hydraulics of the water body that overlays them, the first program objective must be to determine these characteristics. Most applied studies of sediment contamination can be classified into one of three types:

1. Evaluation of effects of contaminated sediments on water quality, aquatic biota, or human health (directly and indirectly).
2. Remediation of contaminated sediments—either *in situ* or by removal—under various treatments.
3. Characterization of the chemical nature of sediments to be dredged (for example, during the maintenance of navigation channels, harbors, and ports) so appropriate disposal can be arranged.

Sometimes the objective of a sediment study is to determine the concentration of one (or a few) chemical contaminants in a specific area; for example, a marine terminal, recreational boat launch site, or downstream from a mine or other industrial or agricultural activity. In this case, sampling locations can be randomly distributed in areas of fine sediments and that would most likely meet the objectives of the study. If the study is expanded, for example to determine the spatial extent of the contamination, then the sampling locations will need to be revised based on a different set of objectives.

The objective of the baseline sediment contamination study is to establish sediment quality within a water body at a fixed point in time, so that future surveys can be compared to determine the direction, magnitude, and rate of change. Similar to the baseline study is the monitoring survey which involves periodic resampling of sediments, preferably on a regular basis[2]. The monitoring survey has the objective of detecting changes in concentrations and spatial distributions of sediment-bound contaminants using the baseline survey as the reference. In both baseline and monitoring surveys, sediments must always be sampled from areas where *permanent* fine-grained materials accumulate.

An important part of the sampling program is the clear statement of objectives that explain why the program is being conducted. This statement also allows the spatial extent of the survey to be determined and justified.

[2]Statistical time series analyses require regular sampling intervals to produce valid results.

Selection of Sampling Locations

The location of sampling sites for contamination studies depends on current knowledge of the distribution of sediment particle sizes in the study area and sediment transport dynamics. In reservoirs, lakes, and ponds the distribution of different size sediment particles is usually quite predictable and stable. For example, in lakes the finest (smallest) particles settle in the deepest water, and in reservoirs fine particles tend to accumulate on the upriver side of the dam. The situation is much more variable and dynamic in streams and rivers. Fine particles can settle among larger particles where current velocities are slow and stable, or along the banks and in sheltered areas otherwise. The dynamism of bottom sediments is demonstrated by the sand waves in the lower Columbia River which can move downriver as much as 3 ft (1 m) in a day during low flow.

The physical and chemical characteristics of stream and river sediments vary both horizontally across the river channel and vertically in the depth of sediments. This variation should be mapped so that homogeneous areas can be identified. The most important sediment group is that of fine-grained sediments, silts and clays $< 63\mu m$. This particle size class accumulates greater concentrations of contaminants, particularly metals and other inorganics, than do larger particles $> 63\mu m$ (1; 2; 3; 5; 4).

Fine-grained particles also include the organic food particles that support benthic invertebrates in the lower reaches of rivers. These animals are, in turn, the preferred foods for salmon smolts migrating to the ocean, resident fish species, and many birds and amphibians. Because of all the physical, chemical, and biological characteristics of these very small sediment particles they should be the focus of all sediment contamination sampling programs.

However, unless all collected sediments are in the same small size class contaminant concentrations cannot be directly compared among locations. The presence of coarser sediments (such as sands $> 63\mu m$, which are very common in rivers) effectively dilutes the concentrations of contaminants such as metals and trace elements that are associated with particles $< 63\mu m$. To compensate for this concentration dilution, results must be normalized to a unit size.

Because the distribution of very fine sediments in rivers changes easily and frequently, sampling should focus on natural sediment traps where the fine particles tend to accumulate except for very high flow events: the insides of bends, isolated pockets along the banks, areas sheltered from the main flow, and similar locations. Seasonal variations in flows, land use activities along the banks, point source effluent outfalls, and other factors that affect both sediment particle size distributions and contaminants mean that a carefully designed preliminary sampling effort will greatly benefit the entire survey program.

Number of Sampling Locations

Determining the appropriate number of samples is a time-consuming, potentially-expensive component of the sediment sampling process. After sediment particle sizes and their distribution are established, preliminary samples are collected and analyzed to determine concentration levels and variability. These values (particularly the variability within and among samples) are then used in a statistical procedure to estimate the number of samples required to produce results within acceptable error limits. However, the calculated number of required samples is often unrealistically large, so economic and pragmatic limits are reasonable to impose on the effort. Two additional approaches help maximize the useful information from a less-than-ideal number of sampling locations.

Mapping the concentrations (in both 2D and 3D maps) permits increased understanding of how both sediments and contaminant concentrations are spatially distributed. The application of map algebra to the data on sediment particle sizes, contaminant concentrations, channel (or reservoir) morphometry, effluent outfall locations, and other data of interest in the basin reveal patterns and relationships that are not obvious from the raw numeric data or descriptive statistics.

Beyond map algebra are spatial statistics (also called geostatistics; see, for example, (6)). These are powerful tools that permit us to calculate spatial autocorrelations (that is, how closely do measured contaminant concentrations depend on the proximity and direction among sampling locations), kriging to account for local values, assessment of local and spatial uncertainties, spatial regressions (cause-and-effect analyses), and other useful information that help decision-makers to conclusions that are technically sound and legally defensible.

Analysis and Interpretation of Data

Parametric exploratory and descriptive statistics reveal limited useful information from the sampling program. While many regulatory programs and statutory threshold standards require us to know the average concentration of a substance across the sampling area, this information has limited value. It is more valuable to know how concentrations are spatially distributed across this area. The use of spatial analyses and statistics help determine how many sampling locations are needed (and where they should be located) and in converting the raw laboratory results of concentration into meaningful information by incorporating the spatial and temporal components of data into the analytical results. Two analytical approaches are appropriate.

Spatial Analyses and Modeling

Spatial analyses and modeling apply terrain, hydrological, and fluvial geomorphic processes to understanding the distribution of sediments and contaminants in specific systems. Terrain (or topography) is available as digital elevation models (DEM) at the appropriate scale and area. These data may be augmented by LIDAR[3] data, particularly for bathymetric characteristics within a river channel. Combining information on topography, hydrology, stream network geometry, and channel morphometry in the appropriate spatial models provides insights into the dynamics of the system and helps to explain why sediments and chemical concentrations are observed at specified locations. There are multiple approaches to combining these data in meaningful ways so project-specific objectives and goals can be robustly addressed.

Spatial Statistics

Natural ecosystem data are distributed in space and time; this can be shown on maps and analyzed with spatial models. Spatial statistics augments the knowledge and insights extracted from measured data by statistical tools that quantify the relationships among attributes, location, and time. Until the late 1980s, spatial statistics was considered a means of describing spatial patterns and interpolating attribute values at unsampled points. A current application of spatial statistics is to measure the uncertainty about unknown values through the generation of alternative images (called *realizations*) that are consistent with measured data.

In parametric statistics there are tools to describe sets of data, to check the degrees of association (correlation) between two or more attributes, determine cause-and-effect (regression) relationships, and make predictions about unsampled areas (the entire population from which the sample has been drawn). Spatial statistics has the equivalent set of tools that incorporate location and time into the analyses of attribute values. Decision-makers have more confidence in their decisions when the appropriate spatial statistical analyses are performed and the results interpreted in clear, nontechnical language.

Applications

Proper sampling and spatial/statistical analyses of aquatic sediments is vital to the assessment and cleanup of harbors, industrial reaches, and other questions and concerns in urban and coastal areas. Similarly, knowledge of soil chemistry and its dynamics is central to brownfield assessments and the redevelopment of former industrial lands. Less obviously, these techniques can be applicable to making better informed decisions by industry, regulators, and politicians regarding a broad range of activities in the natural resource and energy industries.

Questions are always asked about the potential changes in water chemistry and their effects on aquatic biota downstream from waste rock and overburden from mineral mines placed in valleys; effects of hydroelectric and agricultural water diversion or storage dams; grazing allocations and feedlots; agricultural

[3]LIght Detection And Ranging. Similar to RADAR but using light (usually a laser) rather than radio waves. LIDAR data from aircraft can map terrain and bathymetry at a very high resultion and detect elevation differences in centimeters.

activities (including irrigation and pesticide applications); timber harvests and forest management practices; peak, ecological, and channel shaping flows; and other non-urban human activities. Water quality standards based on biological criteria rather than chemical ones also require understanding the functional dynamics of watersheds, stream and river networks, and sediment transport dynamics. Environmental impact assessments under federal and state laws also benefit from examinination of process that produces the observed structures. Today, measurement and analytical tools are much more capable, accurate, and powerful than those available even as recent as 20 years ago. Not taking advantage of these advances for project planning and implementation, environmental regulation, and resource allocation policy decisions raises costs, requires increased time, and reduces opportunities.

References

[1] Ackerman, F. 1980. A procedure for correcting the grain size effect in heavy metal analysis of estuarine and coastal sediments. *Environmental Technology Letters* **1**:518ff.

[2] de Groot, A.J., K.H. Zschuppe, W. Salomons. 1982. Standardization of methods of analysis for heavy metals in sediments. *Hydrologia* **92**:689ff.

[3] Förstner, U. 1982. Accumulative phases for heavy metals in limnic sediments. *Hydrobiologia* **91**:269ff.

[4] Mudroch, A. 1984. Particle size effects on concentration of metals in Lake Erie bottom sediments. *Water Pollution Research Journal of Canada* **19**:27ff.

[5] Horowitz, A.J. and K.A. Elrick. 1988. Interpretation of bed sediment trace metal data: methods for dealing with the grain size effect. In Lichtenberg, J.J., J.A. Winter, C.I. Weber, L. Fradkin, Eds. *Chemical and Biological Characterization of Sludges, Sediments, Dredge Spoils, and Drilling Muds*. ASTM STP 976. American Society for Testing and Materials, Philadelphia, PA. 114 pp.

[6] Goovaerts, P. 1997. *Geostatistics for Natural Resources Evaluation*. Oxford University Press, New York. 483 pp.