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Environmental quality: changing times for sediment programs

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ABSTRACT There is a growing acceptance that effective water resource management requires integration of institutional, policy and program elements that deal with water and sediment quantity and quality issues. Because the role of sediment transport in the field of water quality management, and the complex interactions between sediment quality and quantity in point and nonpoint source management policies and programs is now widely accepted, many sediment agencies are attempting to deal with these new realities. Although the principles for establishing and evaluating sediment network data for the purpose of physical sedimentation issues are well known, difficulties frequently arise when environmental quality issues are grafted into existing programs of sediment agencies. These difficulties follow from the presumption that sediment quality can be handled as an extension of existing sediment quantity protocols. Sediment agencies must consider alternative types of data and reassess the cost and information efficiencies of programs that produce highly accurate physical data at small numbers of sites.

INTRODUCTION

Traditionally, sediment agencies measure three parameters -- discharge (stage), suspended sediment concentration and, less frequently, particle-size distribution of suspended and bed sediments. These parameters are reported within small margins of error. While important scientific questions remain in the field of sediment transport and delivery, the nature of these questions has been articulated for more than twenty years and do not materially change the fundamental precepts of sediment monitoring. An important recent development in the sediment network field has been the systematic analysis of data records with the objective of rationalizing and reducing record length commensurate to the need for data (Day, 1988). This type of analysis addresses the question of cost of data collection versus the need for information.

There is, however, a growing acceptance that effective management of water resources requires integration of institutional, policy and program elements that deal with water quantity and quality issues. Because the role of sediment transport in water quality management, and the complex interactions between sediment quality and

quantity in point and nonpoint source management policies and programs are now widely accepted, many sediment agencies are attempting to adapt to meet these new information needs. Fundamentally, these concerns arise because of the now, well-known relationship between chemical transport and fine-grained suspended sediment (Chapman et al., 1982). For sediment quality purposes, sediment agencies must adapt to a profoundly different set of constraints. The first is the problem of inadequate science; the second is a fundamental rethinking of the nature of measurement error relative to natural variance in stream systems and how to effectively apply uncertain data to complex environmental management issues; the third is a rethinking of the types of data, especially approximate and proxy data, that can be easily collected at large number of sites rather than current practice of highly detailed data at few sites.

SCIENTIFIC ISSUES

There are, of course, a host of scientific issues that are in need of attention. Here, I address what I consider to be the most important questions that apply to the ability to collect and use sediment data for environmental quality purposes. It is imperative to note that complete scientific resolution is unlikely; more importantly, it is necessary to know enough about the following scientific questions in order to make judgements about the applicability of the data to the management issue at hand.

1. In-Stream Particle Size

Particle size, especially for the <63 μm fraction is, to a large extent, operationally defined by the particular techniques used. These can range from minimal treatment to complete disaggregation of the sample using chemical and mechanical agents. Sizing apparatus such as the Coulter Counter, Sedigraph and Malvern are inherently destructive in that the sample is mechanically agitated and pumped into the sensor. While there has been considerable indirect observation of the flocculated state of fine-grained suspended matter in rivers (e.g. Ongley, 1981) the true nature of the cohesive fraction (<63μm) is poorly known because of the lack of instrumentation permitting non-destructive, in-situ analysis of the particle distribution.

Using innovative in-situ and non-destructive measuring techniques, Bale and Morris (1987) were the first to show that in-situ size distribution of the fine fraction in an estuarine situation was coarser than the same material after pumping and analysis both as raw sediment and as dispersed sediment. Bale and Morris' observations were indirect in that the size distribution was computed using Fraunhofer Diffraction principles (Malvern Particle Size Analyzer). Droppo and Ongley (1992) were the first to characterize the flocculated state of freshwater suspended sediment using direct analysis procedures. They found that 97% of the <63μm fraction (by volume) was associated with flocs. Subsequently, Droppo and his colleagues (pers. comm.) have found that fine-grained suspended sediment is the characteristic mode of transport in a number of rivers examined in Ontario.

Although not in the domain of traditional sedimentology, the presence/absence of

flocculation may be intimately related to microbial degradation of sediment-associated contaminants. Work of Bell & Albright (1981) demonstrated that 60% of bacterial biomass was associated with suspended particulates in the turbid Fraser River estuary, but declined to 15-39% as salinity increased. Droppo (1989) also found high bacterial counts associated with suspended sediment in an Ontario river. Preliminary evidence in Rao et al. (1988) suggests that bacteria tend to be most associated with maximum floc size. Unpublished work of Ongley et al. shows a lack of downstream continuity of sediment-associated organic contaminants in the North Saskatchewan River, suggesting that trace contaminant chemistry is being reduced to less than detection levels in the downstream direction. At this time we are unable to explain the mechanisms causing these observations; however, if our hypothesis of floc settling (below) and biochemical degradation is correct, particle size characteristics become important controlling factors of chemical transport.

2. Downstream Transport

The presence of flocculation in the cohesive fraction has some methodological and practical implications. Preliminary evidence suggests that the settling behaviour of flocculated sediment is sufficiently different from primary mineral sediment that conventional transport models applied to fine-grained sediment transport may be seriously in error. Krishnappan (reported in Ongley et al. in press) has demonstrated that unflocculated material will be transported with minimal loss over a reach of 1200m, whereas the material is completely deposited within 600m if one assumes flocculation. Because the in-stream concentration of suspended sediment does not change, one must conclude that there are sediment deposition/replacement processes operating. The same conclusion may explain observations by Blachford and Ongley (1984) and Ongley (unpublished) who found systematic reductions in suspended sediment-associated chemistry in the downstream direction in several large prairie rivers of Canada. There was no evidence for a shift in chemical equilibria nor was there sufficient change in suspended sediment concentration that might cause the dilution of sediment chemistry observed by Axtmann & Luoma (1991) in Clark Fork River, Montana.

The practical implications of these findings for predicting chemical transport, fate and effects is obvious. Understandably, sediment networks currently provide no information about the in-situ particle-size distribution. While it is not recommended that sediment agencies change their particle sizing techniques, there is a need for collaboration between research and sediment agencies to provide approximate information on the difference between particle size distributions determined by their routine methods, and the in-situ distribution. This information will permit modellers to assess the potential for error in predicting sediment-associated chemical transport.

More generally, sediment agencies will have to consider the role of sediment data within an information context. For example, sediment and, more particularly, suspended sediment, play an essential role in chemical transport not only through physical processes such as sedimentation and remobilization, but also because of the role of sediment in equilibrium processes operating within the water column. Furthermore, chemical "information" changes in the downstream direction for many

reasons other than physical settling, biochemical and chemical processes as noted above. Ongley (1987) noted that "information transfer" (I_t), that is, the ability to deduce upstream causes or downstream consequences from a site-specific chemical value (often the purpose of collecting sediment and chemical data) for control and/or prediction purposes, can be depicted as:

$$I_t \sim \frac{\text{(Information from source)}}{\text{(Information introduced in transit)}} - \text{Loss} - \text{Lag}$$

This formulation attempts to illustrate that chemical information, after it is introduced into the water column at some point in the basin (e.g. point source or tributary input), is modified during downstream transport by factors such as additions of chemistry or shift in partitioning due to inputs of sediment, loss due to factors such as sedimentation, volatilization, and temporal lagging when the sediment is temporarily deposited, or chemistry is temporarily lost in transit due to biological uptake. Our field programs in which sediment chemistry is sampled as time-of-travel (Lagrangian sampling) demonstrate such pronounced downstream shifts in sediment-associated trace metals that it can be very difficult to make any statement concerning upstream cause or downstream consequence of site-specific sediment chemistry.

For sediment programs, the potential for fine-grained sedimentation and replacement, and profound shifts in sediment-associated chemistry in the downstream direction, must give cause to question whether current data programs are especially useful in resolving these important transport issues. In Ontario, for example, nonpoint source phosphorus abatement programs focus on land use management, yet it is unknown whether phosphorus transport (mainly a sediment-related phenomenon) is a time-of-travel phenomenon, or whether it is highly discontinuous. If the former, on-land abatement programs can be expected to reduce phosphorus input into the Great Lakes. If the latter, there may well be a distance decay function implying that on-land programs have their maximum impact when close to the river mouth, and decreasing impact as one moves upstream. Clearly this is a very significant point for cost-effective land-use management policies. In the Great Lakes basin, for example, extensive chemical sampling programs permit computation of river-mouth phosphorus loads, but neither chemical nor sediment programs allow one to address the science of transport which is the key to making judgements on efficacy of alternative land-use policy proposals. In view of the hundreds of millions of dollars spent on phosphorus abatement, data programs should be capable of providing information for such assessments.

3. Spatial and Temporal Variability

The temporal and cross-sectional variability of suspended sediment concentration is well known. What is not well known is the variability of suspended sediment-associated chemistry. Because most water quality programs can afford only discrete interval (e.g. once per week/month) single point data, knowledge of spatial and temporal variability becomes most important when attempting to interpret such information for management purposes.

TABLE 1   Cross sectional variability (%) in trace elements on <63μm
suspended sediment. (calculated from data in Horowitz et al., 1990).

	<63μm (ppm)	Cu %	Zn %	Pb %	Cr %	Ni %
Arkansas River (5/11/87) (sampled width = 90 ft. five verticals)						
Time 1	12	73	25	26	23	65
Time 2	14	48	08	23	16	46
Time 3	09	70	12	09	64	78
Cowlitz River (4/20/87) (sampled width = 325ft. five verticals)						
Time 1	10	41	27	33	69	63
Time 2	22	51	25	29	92	90
Time 3	13	31	40	29	87	85

% variability is calculated as (Max. conc.- Min. conc.)/Max. conc.

In a detailed study of suspended sediment trace element chemistry, Horowitz et al. (1990) found substantial differences both in time and within the section. The variability is summarized in Table 1. Sampling was conducted under steady state conditions. Each set of cross-sectional samples are simultaneous; each set of samples (time = 1-3) is approximately 30 min. apart. The data are instantaneous and demonstrate the large variability that can occur within single cross sections. Most importantly, the variability appears to be unrelated to changes in amount of the fine-grained fraction and is not systematic in time or space.

In a similar type of study, Droppo (unpublished data) shows that samples taken for metal chemistry under steady state conditions at ten minute intervals from the centroid of flow, can vary by up to a factor of x2. Droppo's values are calculated by the method of differences wherein particulate chemistry is the difference of Total (whole water analysis) minus filterable. It is probable that some of the variability noted by Droppo is an artifact of the methodology, nevertheless the method is commonly used by water agencies and whether or not the variability is method dependent or is sediment dependent is irrelevant when such data are used to calculate sediment-associated chemical flux.

VARIABILITY AND UNCERTAINTY

The question of variability and uncertainty in the interpretation of data programs is often ignored by monitoring agencies. There are two sides to this question; (1) whether or not the management issue at hand requires exact information, and (2) whether "accurate" data are, in fact, accurate at all. The first question is not addressed here as

it is dependent upon the particular management problem. In general, large area issues (e.g. land use management) are incapable of exact analysis but can be adequately addressed by approximate information (below). The second question is more fundamental to how agencies use data for extrapolation and interpretation.

"Accuracy" in chemical monitoring programs tends to be focused on laboratory programs. Often, effort is made to address field sampling errors. Nevertheless, chemical programs must use interval data (daily, weekly monthly samples) and, often, from a single point in the cross-section. Sediment agencies make great effort to produce highly accurate sediment measurements which usually demonstrate the variability of sediment concentrations, including the chemically active fraction, in the cross section. The issue is whether the interpretation of "accurate" data produces accurate information? We have already noted that sediment-associated chemical data can vary over factors of x2 and x3 in a single cross section under steady state conditions. One wonders, then, whether single point chemical data, necessarily taken without detailed cross sectional information due to cost does, in fact, accurately characterizes the stream chemistry. The answer is usually unknown but experienced field geochemists regard a 30% error as highly probable (Mudroch, pers. comm.).

Ongley (1991) examined this question in the context of calculations of in-stream chemical loads. The loading concept is often used to make management judgements about chemical control measures in river basins (e.g. phosphorus abatement in the Great Lakes basin). Because load is the product of discharge times chemical concentration (on sediment or otherwise), Ongley wished to examine the reliability of loads calculated by interval data. Using continuous data as the benchmark, Ongley was able to show that loading values were highly variable for sediment-associated substances but, more interestingly, providing one knew the range of real data, one could approximate actual loads using random numbers for chemical concentrations. The object, of course, is not to suggest that data programs rely on random numbers, but rather that there is such variance in in-stream conditions, that "accurate" chemical data is, in fact, quite inexact when interpreting in-stream conditions. The same argument can be made for use of detailed physical data in sediment programs for quality purposes because of the difficulties in extrapolating in time from periodic or interval cross sectional measurements. Again, the issue is not that detailed data are not useful; rather, such data tell us much about the scientific question of variability, but are of limited use for practical environmental quality issues that require temporal extrapolation such as loadings calculations.

PROXY AND APPROXIMATE DATA

Managing environmental impact of organic and inorganic substances involves a large range of point and nonpoint source issues for which sediment is often a central or contributing factor. An important question for sediment agencies is whether the management issue at hand requires exact data, or is capable of resolution with approximate data. Moreover, one must also ask whether the cost of collecting exact data from a small number of sites, together with the implicit cost of foregone data (ie. essential data not collected because of cost of maintaining a few detailed sites), is detrimental to the larger purposes of environmental management for which the data

program was established. Experience in the Great Lakes Basin indicates that large area management decisions such as land use controls, phosphorus abatement strategies, etc., that require sediment and chemical information, require large amounts of long-term, spatially distributed data; the issues, however, can be addressed at a suitable level of resolution by approximate information, especially in view of the known errors in extrapolating in time and space from very limited, highly specific data. Alternatively, site-specific issues usually require more detailed data but which need not be collected over long periods of time nor over large areas.

Sediment agencies characteristically produce very detailed information for a small number of sites. For environmental quality purposes, however, the high level of uncertainty in interpreting field and laboratory data for management purposes suggests that much greater economies and more useful data could be generated at large number of sites if agencies utilized approximate and proxy data.

1. Suspended Sediment Concentration

Next to discharge measurements, suspended sediment concentration is the most important parameter for determining chemical flux. In many (but certainly not all) rivers of the world, the <63μm fraction is the predominant component of the load. The vertical and cross-sectional changes in suspended sediment concentration is well known; however, work of Guy & Norman (1970), Culbertson et al. (1981), U.S. Soil Conservation Service (1983), Ongley (1982) and Ongley et al. (1982, 1990) suggests that in many rivers the vertical variability is sufficiently small that single point sampling is a reasonable approximation of the vertical profile. More important is the temporal variability that is unavailable in most sediment programs. Because the wash load component (~cohesive fraction) is a non-capacity load, temporal variability is not easily predictable in any one river and can demonstrate profoundly different relationships with discharge within different rivers (Walling & Moorehead, 1987). Continuous proxy data using real-time turbidity sensors is an economical measure of approximate concentration of fine-grained sediment (e.g. Sanmuganathan & Bolton, 1984). Such data are valuable both for understanding sediment conveyance processes and for evaluating sediment-associated chemical loads in rivers where the bulk of the suspended material is <63μm. Turbidity data can not be used in all rivers (e.g. brown waters) but undoubtedly have broad utility in many parts of the world.

2. Chemically Active Fraction

Knowledge of the proportion of the suspended load that is chemically active is essential for determining chemical transport. Also, this proportion is often used to normalize sediment metal chemistry in order to account for matrix effects.

There are many views on the appropriate size fraction that is primarily associated with chemical transport. Conventional wisdom suggests that either the <63 or <125μm fraction is most closely associated with trace metal transport. Horowitz and Elrick (1987, 1988) found in their study of stream bed sediments in the United States, that the <63 and <125μm fractions were comparable and were more closely correlated with

trace metal chemistry than either the <2 or <16μm fractions. For practical purposes, the appropriate particle-size range is easily determined. Once established, a useful variable is the proportion of the suspended sediment more than and less than this value. This is easily determined by a combination of filtration (total suspended sediment above 0.45μm) and sieving (at the <63 or <125μm boundary), or by instrumental methods that provide almost instantaneous results using ambient concentrations of suspended sediment. Furthermore, this variable eliminates much of the need to carry out sub-sieve particle-size analysis and can be obtained routinely at many locations.

While sediment-associated metal chemistry is not entirely predictable, experience suggests that, for practical purposes, relationships can be generated that equate suspended sediment chemistry with sediment concentration such that continuous records of turbidity, together with knowledge of the proportion of the suspended load that is <63μm (or <125μm), will be more accurate in predicting sediment-associated chemical transport than current water chemistry and sediment measurement programs.

3. Particulate Organic Carbon

Unlike trace metals that are associated with mineral sediment, organic contaminants are primarily associated with the particulate carbon component of the sediment. In most river systems the particulate carbon component tends to be low (<10%); nevertheless, the use of percent carbon to normalize organic chemistry in rivers of differing carbon content is essential if site comparisons are to be made. Particulate organic carbon content should be considered for inclusion as a standard variable within sediment programs that are linked to organic chemical management issues.

4. Partitioning Coefficients

Because of the well-known relationship between many of the priority contaminants and sediment, sediment programs can play an essential role in providing useful estimates of presence and flux of these substances. In practice, however, organic and inorganic chemistry is normally carried out on whole or filtered water samples with the result that agency records tend to be filled by ND's (not detectable) when, in fact, the chemistry is present. For example, Ongley et al. (1988) demonstrated for a wide range of contaminants that not only does water analysis fail to characterize the chemistry of the water column, but also misses much of the toxicity. They recommended that analysis should be carried out directly on dewatered suspended sediment.

Although sediment is the preferred phase for chemical analysis, the in-stream chemical load is often largely in the soluble phase when the suspended sediment concentration is low. Conventional solution data, however, often indicate "not detectable" concentrations and subsequent loadings calculations would be unrealistically low. However, approximate estimates of solution concentration can be made from a knowledge of partitioning coefficients when the sediment chemistry is known. For organic contaminants this is relatively straight-forward. For example, using octanol-water coefficients relative to expected adsorption to suspended solids (Maguire,

TABLE 2 Percent adsorbed to suspended matter for selected organic compounds.

Susp, Sed.	mg/l	10	100	1000	10000
Lindane	(3.9)	0	2	30	80
PCB	(5.0)	4	30	83	97
Chlordane	(6.0)	30	80	100	100
Mirex	(6.9)	80	95	100	100

( ) octanol-water partitioning coefficient; values for PCB
  range between 5-7.

reported in Ongley et al., in press), Table 2 indicates the proportion of the load transported on the sediment phase for a several common organic compounds. This proportion is applied to the measured sediment chemistry of each compound, and pro-rated for the suspended sediment concentration in the raw water to obtain the estimated concentration in the aqueous phase.

A similar relationship can be developed for sediment-associated metals, however the partitioning relationship is not so straight-forward due to variability in chemical, physical and mineralogical controls over the sorption process. Nevertheless, a first approximation for solution chemistry can be made if one knows the pH of the sampled river; knowledge of, for example, carbonate and iron content of the sediment, can significantly improve the approximation.

CONCLUSIONS

On the basis of what we now know about the interactions between sediment transport and water quality, and in light of the known uncertainties in applying sediment quality data, one can make a number of simplifying recommendations for sediment quality monitoring programs. The rationale lies in the fact that the type of detailed information normally produced by traditional sediment programs is (a) often not especially useful for management of environmental quality issues, (b) most environmental quality issues are not only incapable of exact analysis for reasons of inexact knowledge but also because of a high degree of variability in the river system which frustrates the use of "exact" data, and (c) it follows that many management decisions, requiring only good judgement based on knowledge of probable consequences of any particular decision, can be made from approximate information.

1. For environmental purposes (in contrast to geological purposes) agencies can restrict themselves to the <63μm or <125μm size fraction for chemical analytic purposes providing these fractions represent a significant proportion of the suspended sediment load.

2. For routine sampling, it is essential to know the following: suspended sediment concentration, proportion <63μm (or <125μm), and organic carbon. These can be

obtained quickly and without elaborate sampling apparatus. In conjunction with chemistry or proxy data (below), these three variables are the basis for modelling and prediction of environmental fate and effects. The particle size information can also be used to normalize the sediment chemistry for matrix effects (assuming that the <63 or <125μm fraction is at least 40% of the sample). The known association of certain organic microcontaminants with organic carbon suggests that organic carbon should be included as a primary parameter.

3. Unless one is carrying out cross-sectional studies of sediment characteristics, it is enough to take a single composited vertical sample from the centroid of maximum flow. This assumes the river is relatively evenly mixed. Some work suggests that a near-surface sample may be quite satisfactory for the chemically active fine-grained fraction.

4. Sediment agencies should seriously consider using real-time sensing of turbidity on the grounds that temporal variability is usually much more important than occasional detailed knowledge of cross-sectional variability.

5. For loadings purposes, the overwhelming influence of discharge makes small errors or uncertainty in chemical data, almost irrelevant. For this reason, agencies should focus on accurate discharge measurement and attempt to obtain as much approximate information on sediment quality attributes as is possible.

6. Because of potential for large change in sediment-associated chemistry in the downstream direction, agencies should exercise great caution in projecting at-a-section information either downstream in terms of effects, or upstream in terms of causation.

7. Although the change in sediment chemistry relative to the hydrograph (e.g. storm or seasonal hysteresis) has not been systematically investigated, loadings values can be reasonably approximated by characterizing seasonal in-stream sediment chemistry with a small number of samples.

8. Water quantity agencies historically focus on producing highly accurate but, for reasons of cost, spatially and/or temporally infrequent information on suspended sediment. For environmental purposes, agencies need to shift to higher spatial and temporal density but with reduced accuracy using, for example, remotely monitoring information such as turbidity applied to periodic survey data on sediment chemistry.

9. Water quality agencies are finding that fixed-site monitoring is often less effective than intensive but infrequent surveys. This approach should be adopted by sediment agencies for establishing approximate relationships for sediment chemistry, toxicology, turbidity, in-stream particle size, etc.. These approximate relationships will often prove to be quite satisfactory for extrapolation to sites with real-time data (e.g. turbidity) for environmental management purposes.

10. Water quality and quantity agencies should establish joint investigative programs to assess (a) the scientific questions relative to sediment quality, but also (b) to establish the minimal level of routine information and acceptable levels of variability that is acceptable for management purposes.

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