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FLUX OF SEDIMENT-ASSOCIATED CONTAMINATION

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Terminology

Advection: the process of mass transport due simply to the flow of water in which the mass is dissolved

Anthropogenic: caused by human activity

Benthic: living on the surface of bottom sediments in a water body

Bioaccumulate: the net accumulation of a chemical in and on an organism from all sources including water, air and solid phases of the environment (solid phases include food and sediment)

Bioturbation: the disruption of sediments due to the movement of biota

Diagenesis: the sum total of physical, biological and chemical processes that bring about changes in a sediment, such as compaction, bioturbation, diffusion, biodegradation, dissolution and precipitation

Diffusion: the net motion of matter resulting from the random motion of individual entities, such as ions

Dispersion: a process of fluid mixing that causes a zone of mixing between two different fluids

Downwelling: the movement of surficial freshwater into sediments and groundwaters

Macrofauna: organisms visible without magnification

Macroinvertebrate: organisms without a backbone that are visible without magnification

Meiofauna: organisms that are > 0.063 and < 1.00 mm in size

Oligochaetes: freshwater worms that live in sediments

Upwelling: the movement of freshwaters rising out of sediments

Sediments have long been recognized as a critical compartment of aquatic ecosystems where natural and anthropogenic chemicals accumulate. This accumulation of particulate and dissolved, organic and inorganic materials makes sediments a centre of biogeochemical cycling and a base of the food web. The benthic microbial, meiofaunal and macrofaunal communities can reflect sediment quality within a given system, which in turn reflects the quality of the watersheds that contribute to the system. Therefore, a tremendous amount of effort has been focused on how to properly assess the quality of sediments, particularly in environmental risk assessments and site remediation projects.

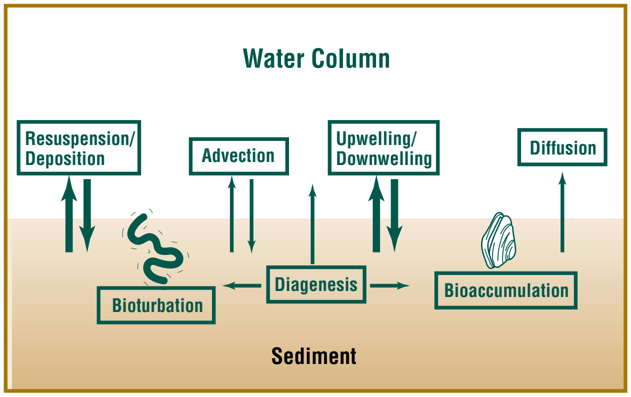

Figure 1

Schematic of flux processes between sediment and water compartments

Sediments typically are thought to be reservoirs, representing long-term accumulations of organic and inorganic depositional materials. They often are viewed as being stable, with little variation occurring through time. While this may be true to some degree, it certainly is not the case for many freshwater and coastal marine waterways. Sediments and their constituents often are dynamic components of the environment that can exhibit significant spatial and temporal movement over periods of hours to months. For example, surficial sediments are often resuspended and moved during significant storm or high flow events. This causes sediments to displace to other sites with both episodic and long-term exposures to organisms during and following the event. This "flux" of sediments may or may not have significant impacts on the risk assessment process, which can be both multi-faceted and site-specific.

It is now clear that the issue of flux (i.e. transport) of sediment-associated contamination is complicated and contentious, and has tremendous implications on the risk assessment and remediation process, as evidenced by some recent Environmental Protection Agency Superfund projects to clean up hazardous waste sites in the United States. Without knowing the extent of sediment flux, one cannot accurately assess or predict exposures and effects from sediment-associated contaminants, both at the site and in down-current areas.

What is Sediment Flux?

Sediment flux is the movement of sediments, their constituents or both from one part (i.e. compartment) of the aquatic ecosystem to another. This may involve movement of particles or dissolved materials from bed sediments to overlying waters with possible redeposition or movement of surface or ground waters in and out of the bed sediments (Figure 1). Sediment flux has been most widely known as sediment transport or fate; however, these terms do not accurately reflect the many flux processes that may exist within a site.

A variety of processes can cause sediment flux (Figure 2). The primary flux processes are: resuspension (erosion) and deposition; bioturbation; advection; upwelling/downwelling; diagenesis reactions; and diffusion. In general, the likelihood for movement of sediment-associated contaminants tends to follow the order in which they are presented here, with diffusion resulting in the least movement. Most sediment fate models focus on only one of these processes and use hydrological resuspension/transport models, or they assume that diffusion dominates. These single-process models often are based on crude assumptions and lack adequate site calibration of dynamic conditions, groundwater–surface water interactions and nonpoint source inputs.

Sediment Flux Processes
Resuspension and Deposition
Bioturbation
Bioaccumulation
Advection
Upwelling and Downwelling
Diagenesis reactions (e.g. sequestration, biotransformations)
Diffusion

Flux Exposure Assessment Tools
Integrated models*
Mini-piezometers for measuring upwellings/downwellings
Multiple gradient wells
Seepage meters
In situ caged exposures of organisms to surface water and sediment-water interface
Semi-permeable membrane devices (SPMDs)

* *Erosion, transport, bioturbation, upwelling/downwelling and diffusion*

Figure 2

Aquatic ecosystems and movement of sediment-associated contaminants

For example, riverine environments are often very heterogeneous, having a wide range of sediment grain-size distributions, which may be mixed or have variable patchiness. Small-grained sediments (e.g. clays) may become embedded between larger grained sands, gravels and cobble or settle in depositional areas and become compacted to varying degrees.

Sporadic storm events result in increased flow (power), which may resuspend (erode) sediments and move them downstream. The degree of sediment erosion depends on the site hydrodynamics (current patterns and power), the degree of compaction, presence of other larger particles and the particles' physicochemical characteristics. These factors can vary markedly over areas of metres in a stream, and change following each storm event. In addition, the magnitude, frequency and duration of storm (hydrological) events vary and are not easily predicted.

Some areas of the river will have dense benthic macroinvertebrate communities, composed of species (e.g. crayfish, bivalves, oligochaetes) that can mobilize sediment contaminants via bioturbation from several centimetres depth (or metres in marine systems) to overlying waters. On the other hand, other sites may be dominated by non-burrowing species, or may be devoid of macrofauna; under these conditions, bioturbation may not be an important factor. Organisms associated with sediments, or that feed on benthic organisms, may also **bioaccumulate** sediment-associated chemicals. (For more information on bioaccumulation, see Fact Sheet No. 8.) If these chemicals are not metabolized and accumulate in the organisms' tissues, they may be transported off-site or to higher levels of the food chain.

It is not uncommon to find significant groundwater–surfacewater interactions (GSI) occurring near the banks of many riverine systems. These typically may be **upwellings** of groundwater or **advection** through sediments into overlying surface waters or vice-versa. Upwellings may revert to downwellings (and vice-versa) depending on snow or rainfall events. At GSI sites, pore (interstitial) waters are not in equilibrium with their surrounding sediments, as is the assumption in **diffusion** models and equilibrium-based sediment quality guidelines. Rather, pore waters at GSI sites reflect the chemistry of the ground or surface waters that are passing through the sediments. However, in depositional sediments where there are no upwellings or downwellings, diffusion may be the dominant process affecting pore waters. Finally, chemically and biologically driven reactions that comprise **diagenesis** result in changes to inorganic and organic compounds and may increase or decrease their bioavailabilities (how metabolically available they are). These processes are very site-specific and difficult to predict. These various flux process issues pose a significant challenge to both the modeller and the risk assessor when trying to characterize exposure and effects relationships.

Predicting Sediment Transport and Flux: Challenging Issues

The hydrodynamics of lakes, reservoirs and coastal tidal areas are dominated by wind and waves, seiche motion (very long-standing waves in lakes) and, in estuaries, density-driven circulation. However, river and stream hydrodynamics are driven by high flow events. Within these aquatic systems are cohesive (silts and clays) and noncohesive (sand and gravel) sediments. The cohesive sediments are the most important when assessing stressor loadings since chemicals tend to accumulate in fine-grained sediments and they are most easily resuspended. The resulting impairment to the ecosystem can be due to chemical exposure (from contaminated solids or desorbed chemicals) or stress from physical abrasion, clogging or smothering of organisms.

Surficial sediments can be easily resuspended due to their proximity to turbulent stress and because deeper sediments are more consolidated, as indicated by decreased porosity. Additionally, some surficial sediments take on an armoring effect as clays and silts embed in larger grained sand and gravel. This cohesive bed armoring and erosion/resuspension potential can be quantified in the lab and estimated in the field (e.g. Graham et al. 1992; Amos et al. 1992; Tsai and Lick 1986; Ziegler and Nisbet 1994).

The process of resuspension occurs due to high bottom shear stresses from overlying water turbulence. The degree of resuspension (depth of scour) during a high flow event (or large waves) is determined by evaluating bottom shear stress and the sediment bed's erosion properties. It is well established that the rare large storm events are extremely important, where a nonlinear relationship exists between resuspension potential and bottom shear stress (e.g. Lick 1992). River current velocity can be crudely estimated using the empirical relationship between flow rate and velocity. Bottom roughness and friction factors for cohesive sediments also can be estimated. So, bottom shear stress can be calculated using crude estimates of bottom friction factors and velocities for currents or waves, water density, time after deposition, wind speed, fetch and depth.

However, sediment stability and flux is site-specific. Site-specific conditions differ substantially in regard to resuspension properties (Ziegler and Nisbet 1995; Roberts et al. 1998) and should be characterized using field and/or laboratory evaluations of resuspension (e.g. using a shaker (Tsai and Lick 1986)) to reduce the uncertainties associated with crude assumptions. Otherwise, estimates of resuspension may be off by orders of magnitude.

State-of-the-science sediment transport models use mechanistic formulations developed from experimental and site-specific data to describe cohesive resuspension and deposition processes. These models require calibration, validation and sensitivity analyses to ensure accuracy and precision. Some popular models that have been used to assess contaminated sediments include SED2D and SEDZL (e.g. Ariathuri and Krone 1976; Ziegler and Lick 1986; Ziegler and Nisbet 1994, 1995; Gailani et al. 1991, 1996). Unfortunately, these models do not account for the other sediment flux processes that may be important.

Which Flux Processes Dominate?

At many sites, the energy of the overlying water flow will be the dominant flux process. If the site is a high-energy site (high flows dominate), then sediments often are course grained, noncohesive, with little adsorption of contaminants (except in mine tailing areas). Here, upwellings and downwellings of ground and surface waters may dominate as a contaminant flux process. At low-energy sites (low flows dominate), depositional, cohesive sediments that can accumulate contaminants are likely. These sites are favoured by burrowing benthic invertebrates. Here bioturbation and diffusion processes are likely to routinely be of importance, with episodic resuspensions occurring due to large high flow events. While upwelling and downwelling can occur here, the sediments' consolidated nature reduces the role of these flux processes.

It is important to realize that all of these flux processes are variable through space and time. Changing seasons bring changes in flow, temperature and organic matter loading, all of which affect each of the flux processes. Episodic high flow events may or may not alter a site's sediment characteristics, depending on the hydrodynamics and bed characteristics. Upwelling and downwelling conditions can reverse over a period of hours to days depending on meteorological and tidal conditions. These conditions and events can be accurately measured by installing inexpensive samplers at the site. Scouring events may remove benthic fauna, thus mitigating bioturbation as a flux process until the sediments have been recolonized. Anoxia (lack of oxygen) will promote release of reduced compounds that were previously complexed and oxidized. Nutrient-rich, depositional sediments may transfer reduced compounds and contaminants up via microbial gas formation. Microbial metabolism and production of critical compounds such as sulphides, ammonia, methylated metals and synthetic organic chemical by-products increases during warmer time periods and with increased loadings of organic and inorganic sources from overlying waters or upwellings. These can be released into overlying waters via several flux processes.

Flux Exposure vs. Biological Effects

The flux processes result in contaminant transport and deposition for time periods ranging from minutes to years. Organisms can accumulate dissolved contaminants that have been released from sediments, or they can ingest contaminants associated with colloidal- to clay-sized particles. Sorption and desorption processes also are complex and dependent on contaminant type and concentration, particle characteristics and site-specific conditions (e.g. turbulence, temperature and microbial metabolism). These processes are markedly important during dredging operations, where an environment of high flow and resuspension is created for short time periods. Reduced metals that are released from the sediments quickly complex with iron and manganese oxyhydroxides and resorb. Even highly nonpolar compounds, such as PCBs, are known to desorb and volatilize, and can move between compartments and in and out of aquatic ecosystems.

These realities mean that organism exposures to contaminants will vary widely depending on the flux processes, meteorological conditions and their behaviour and life history patterns. The term "flux exposure" refers to organism exposures that are directly related to the various flux processes (Figure 2). An organism that burrows into and ingests sediments will be affected by differing flux processes than one that recirculates overlying waters into its burrows. Both types of organisms may be affected by a dominating process such as a high flow, resuspension event or strong upwelling/downwelling.

Accurately predicting exposures and resulting effects to all the aquatic organisms that may be important at a site is a challenge, but can be accomplished with reasonable accuracy using multiple lines-of-evidence (Burton and Pitt 2001). For example, *in situ* exposures of caged invertebrates have been used at several sites to differentiate between stressor source compartments (surface water at low or high flow, surficial sediments or upwellings/downwellings at the sediment–water interface). Cages are briefly positioned in the different compartments during low and high flow conditions and lethal/sublethal responses measured. Exposure is monitored by measuring key physico-chemical parameters in the stream, sediments and cages. Upwelling and downwelling exposures are characterized using mini-piezometers. These data are compared with indigenous biotic metrics, habitat conditions and traditional assessment approaches to better define exposure–effects relationships (e.g. Burton and Pitt 2001; Burton et al. 2002; Greenberg et al. 2002).

Assessing Sediment Flux: A Way Forward

We have significantly increased our understanding of the various biological, chemical and physical processes that control sediment flux. Many of these processes now can be described by basic principles and equations. These, in turn, can be integrated into computer models calibrated with site-specific data. When these model outputs are coupled with site-specific exposure and effects data, a reasonably accurate representation of the aquatic system can be made, enabling well-informed management decisions. In the absence of an advanced, process-integrating model, reasonable assessments of environmental risk should simply characterize exposure and effects at the sediment–water interface during periods of low and high flow and at differing seasons. This simplistic approach links adverse biological effects with relevant system compartments (surficial waters, the sediment–water interface, bed sediments and upwellings/downwellings) during critical time periods, thereby integrating the flux processes with their environmental significance.

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G. Allen Burton, Jr. is the Brage Golding Distinguished Professor of Research and Director of the Institute for Environmental Quality at Wright State University in Dayton, Ohio, USA. He obtained a Ph.D. in Environmental Science from the University of Texas at Dallas in 1984. From 1980 until 1985, he was a Life Scientist with the US Environmental Protection Agency (EPA). He was a Postdoctoral Fellow at the National Oceanic and Atmospheric Administration's Cooperative Institute for Research in Environmental Sciences at the University of Colorado. Since then he has had positions as a NATO Senior Research Fellow in Portugal and Visiting Senior Scientist in Italy and New Zealand. Dr. Burton's research during the past 23 years has focused on developing effective methods for identifying significant effects and stressors in aquatic systems where sediment and stormwater contamination is a concern. His ecosystem risk assessments have evaluated multiple levels of biological organization, ranging from microbial to amphibian effects. He has been active in the development and standardization of toxicity methods for the US EPA, American Society for Testing and Materials (ASTM), Environment Canada and the Organisation for Economic Co-operation and Development (OECD). Dr. Burton has served on numerous national and international scientific committees and review panels, has had more than US$4 million in grants and contracts and has contributed to more than 100 publications dealing with aquatic systems.

Fact Sheet on Environmental Risk Assessment

This is the ninth in an occasional series of *Fact Sheets* to be produced by ICMM on metal-specific issues in environmental risk assessment. Authorship selection and editorial review are coordinated by Dr. Anne Fairbrother of Parametrix, Inc. Each *Fact Sheet* is reviewed for technical merit by Dr. Erik Smolders of Katholieke Universiteit (Catholic University) Leuven, Belgium, and by a panel of experts in metal-related regulatory issues. While the *Fact Sheets* reflect the views of the authors, they are intended to provide an objective review of each topic. ICMM hopes these publications provide insights into complex issues in regulatory science, and welcomes questions and comments.

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