Sediment quality in Australian river basins: a compartmental approach to assessment of a regional sediment-variability factor

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Abstract Sedimentological, geochemical, hydrological, and land use information from major river basins along the east coast of Australia are used to develop a framework for comparative evaluation of regional scale variation in aquatic sediment quality. Textural features of bottom sediment form the basis for assessing bottom dynamics and sediment quality variability in depositional areas of a river basin on a hierarchical basis. Despite local variation in loading and partitioning characteristics of sediment-bound contaminants, regional variation in key sediment quality parameters largely reflects the influence of catchment hydrogeology and land use features. Land scale units used for compartmental assessments closely correspond with major hydrological zones in the drainage basins studied. The compartmental approach to sediment quality assessment is compatible with time requirements for potential natural recovery of contaminated sediment in river basins with diverse environmental flows and land use impacts.

INTRODUCTION

Aquatic sediment forms an integral part of ecosystems in natural and manmade waterways and are known to contain records of past and present urban and rural runoff, chemical discharges, and spills. Consequently, the role of sediment as a sink for accumulation of pollutants and as a contaminant source for potential impact on the quality of receiving waters has received increasing attention in recent years (Burton, 1992).

In Australia slightly more than 70% of the population is clustered around coastal waterways, and awareness of potential risks associated with contaminated sediment relative to water quality and human health have reached a significant level of national interest. Sources of hazardous substances in urban and rural waterways include industrial, agricultural, and mine spoil discharges, treated effluent from sewage treatment plants, and storm runoff (CEPA, 1994; Arakel, 1995). A range of causative processes, such as soil erosion and acidity, flood runoff, dredging, and seepage from shallow aquifers, has been recognized for such entries (Arakel, 1995). Despite expanding knowledge on elevated concentrations of heavy metals and organic contaminants in aquatic sediment of coastal waterways with known sources of contaminant input (Arakel

& Ridley, 1986; Carpenter *et al.*, 1991; Arakel & Hongjun, 1991; Hanna, 1992; Pailles *et al.*, 1993), there is major paucity of knowledge on the nature and the scale of sediment contamination. Thus, synoptic assessment of scales of variability in sediment quality is only possible for a few well studied coastal river basins. These shortcomings highlight the need for a coherent approach to sediment quality assessment and development of quality standards consistent with Australian environmental conditions and land use activities.

This paper assesses regional variability in sediment quality and dynamics with reference to climatic and hydrological conditions, geomorphic setting, and land use activities in selected coastal river basins for which compatible sediment data are available. The paper discusses benefits from compartmental evaluation of sediment quality, particularly for establishing meaningful aquatic sediment quality guidelines for river basins with diverse hydrological and land use features.

Sediment data used in this study relate to eight major river-estuary systems along the east coast of Australia (Fig. 1(a)) that are subject to a variety of human activities within their catchments, including land clearance, agriculture, mining, and urbanization. These river systems fall into two broad climatic zones:

(a) the seasonally wet and dry tropics region extending from north to central coast of Queensland, where predominantly agricultural catchments are subjected to aperiodic cyclone-induced runoff events, and
(b) the climatically temperate warm humid coastal region covering the southern half of the east coast and clustered with major urban centres.

Detailed information on physical and hydrological attributes of these rivers and methods applied for sediment studies are described in Arakel (1995).

SEDIMENT VARIABILITY FACTOR

Heterogeneity in textural and compositional characteristics of fluvio-estuarine sediment has long been recognized as a reflection of natural processes and of a variety of land use activities and anthropogenic inputs (Burton, 1992). With increasing intensity of land use and flow regulation, the influence of catchment hydrology on environmental flow and bottom dynamics of the rivers in Australia has been reduced significantly (Arakel, 1995). The issue of increasing effluent discharge, with a more common incidence of storm runoff in urbanized rivers, is a major area of public concern and scientific attention, particularly concerning the role of aquatic sediment in reducing ecosystem productivity through major shifts in sediment pH, redox potential, oxygen demand, and production of anoxia (cf. Griffiths *et al.*, 1982). Heterogeneity in sedimentary textural characteristics influences the transfer pathway of contaminants via the sediment matrix (Hakanson, 1992; Hanna, 1992; Kennicutt *et al.*, 1994).

The extent to which contaminant loading of aquatic sediment in a river system varies depends on sediment dynamics and thus on the particle size distribution (Arakel, 1995). For this reason, the scale of investigation is paramount in the assessment of process relations in a river basin. The physical-chemical and microbiological processes active at the sediment-water interface that exert an important influence on the distribution pathway of contaminants is best described at the scale of a single depositional unit (e.g. Burgess & Scott, 1992). However, the relative rate of release of toxins from bottom sediment is dependant on efficiency of release of particulate matter and associated contaminants to the water column from the bottom sediment. Thus, an understanding of the hydrological regime and the form and quantity of contaminants available for release from the catchment sedimentary compartments is necessary for an accurate prediction of availability of contaminants to the water column and biota in downstream depositional areas.

For a basin assessment, the significance of contaminant transfer via sediment-water interface depends on the degree of complexity of seasonal and longer-term variation in catchment hydrology as measured by differences in precipitation, physiographic setting, soil characteristics, and permeability of the catchment. The following comparisons of sediment characteristics provide insight into the influence of sediment variability factor on contaminant loading of aquatic sediment in rivers impacted by diverse land use activity.

Trace metals

Seasonal runoff from monsoonal rainfall removes large volumes of soil and eroded sediment from agricultural catchments of Australian rivers by gully and sheet erosion. A feature common to the catchments of southern rivers (Brisbane, Hawkesbury-Nepean, Georges, and Cooks Rivers) relates to the extension of urban sprawl to upper catchment areas; in the case of the Hawkesbury-Nepean River (Fig. 1(b)), urban land use extends to second-order streams in mid catchment areas. As shown in Fig. 1(c) and (d), the sum of trace metal concentrations in the mud fraction of bed sediment in mid-catchment streams is elevated compared with the sum of the same metals in bed sediment from the main channel and estuarine reaches of this river. Highest concentrations commonly relate to streams receiving discharge from point sources of effluent. In urbanized sub-catchments, isolated pools of fine-grained sediment form important repositories for trace metals and nutrients (Arakel, 1995).

In the main channel, and particularly in estuarine reaches of the rivers, turbulent mixing exerts a dominant influence on redistribution of bottom sediment, hence the transfer of nutrients and trace metals to depositional zones in sheltered embayments and tidal creeks. Monitoring of estuarine reaches of the Hawkesbury-Nepean River indicates significant variability in water quality as a function of change in bed concentrations of trace metals and nutrients according to tidal phase at the time of sampling (Arakel, 1995). Concentrations of trace metals and nutrients in suspended matter may reach values several times higher than in bottom sediment depending on the extent of sorting under estuarine conditions (Arakel, 1995). These findings highlight the observation that physical features and geochemical nature of bed sediment provide only an indication of potential impact of sediment on water quality.

Sedimentation features in north Queensland tropical rivers (Johnstone and Proserpine Rivers) are much different and regionally more variable compared with the southern counterparts (Arakel, 1995). In the case of the North and South Johnstone Rivers (Fig. 2(a)), variability in catchment sediment yield is best explained by variability in discharge rates under seasonal flow regimes (Arakel *et al.*, 1989). Field observations from these rivers indicate that despite a gravelly nature of bed sediment in the catchment areas, seasonal and aperiodic storm runoff from the basaltic and granitic terrains in the upper- and mid-catchment areas is probably the main cause for a disproportionate

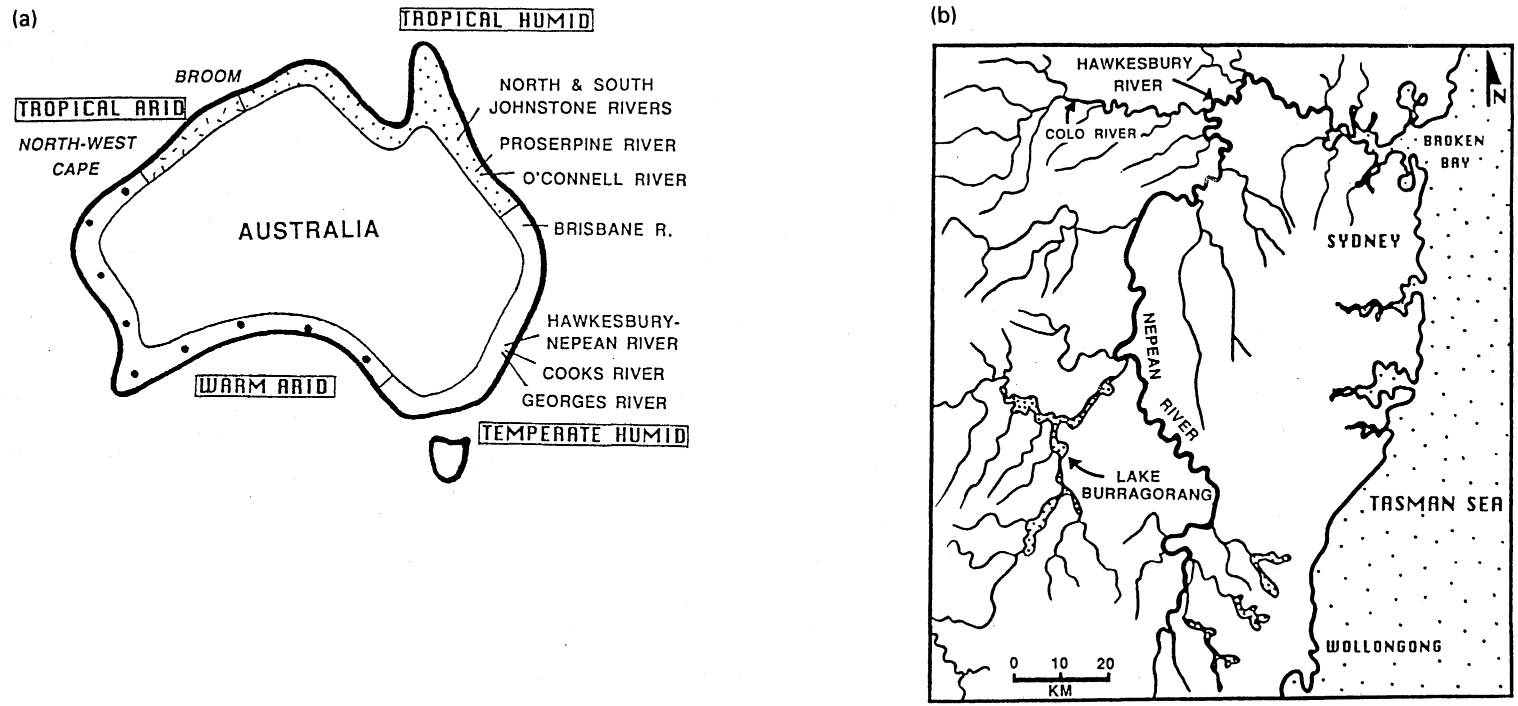

Fig. 1 (a) Location map; (b) regional map of the Hawkesbury-Nepean River.

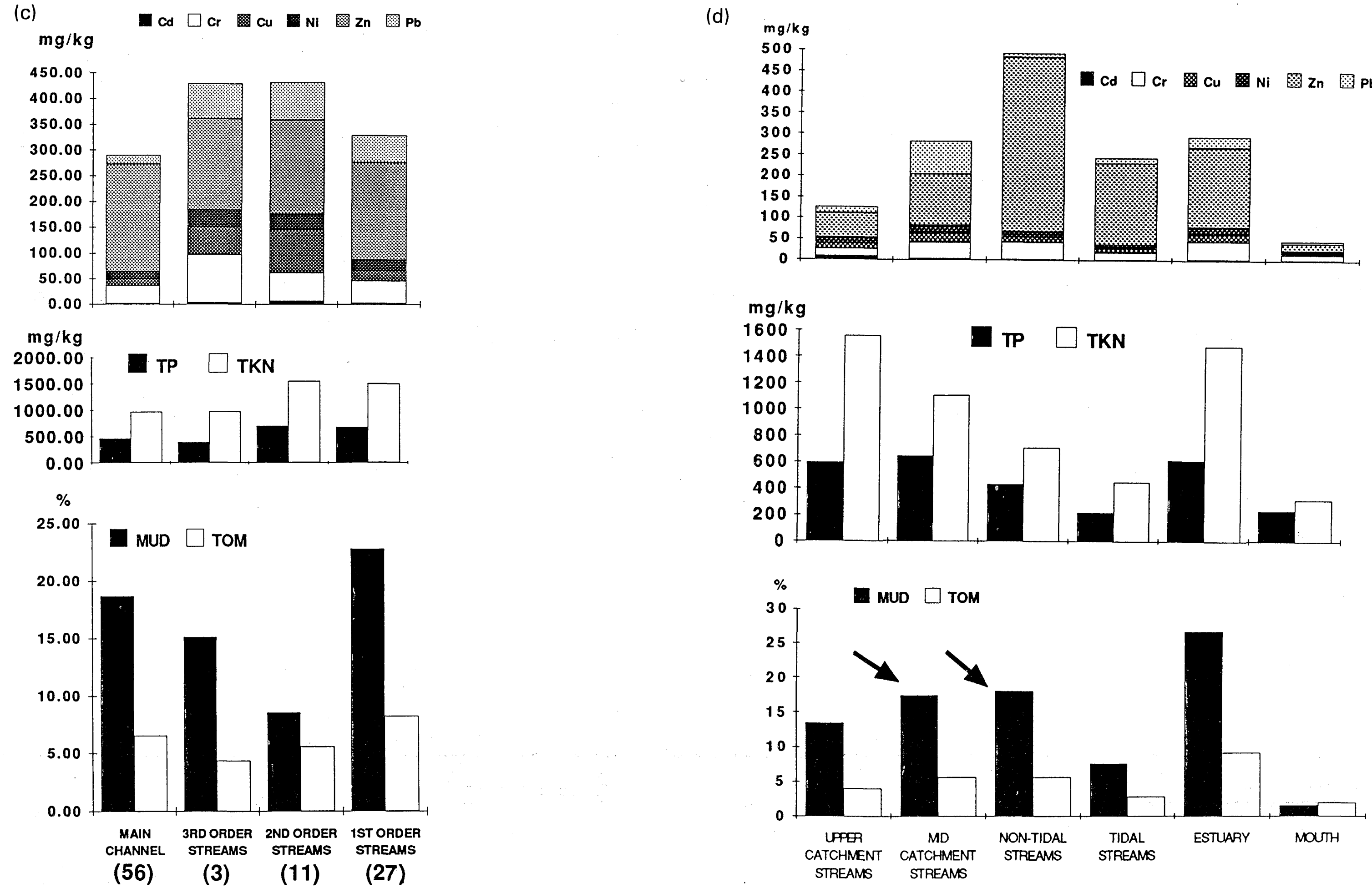

Fig. 1 (c) Cumulated concentration of trace metals, nutrients (TP = total phosphorous; TKN = total Kjeldahl nitrogen), mud content, and total organic matter (TOM) in the main channel and stream systems of the Hawkesbury-Nepean River; and (d) sediment quality data, summarized in (c), shown for different hydrological zones of the river. Arrows in (d) indicate point sources. Numbers in brackets denote number of samples in each group.

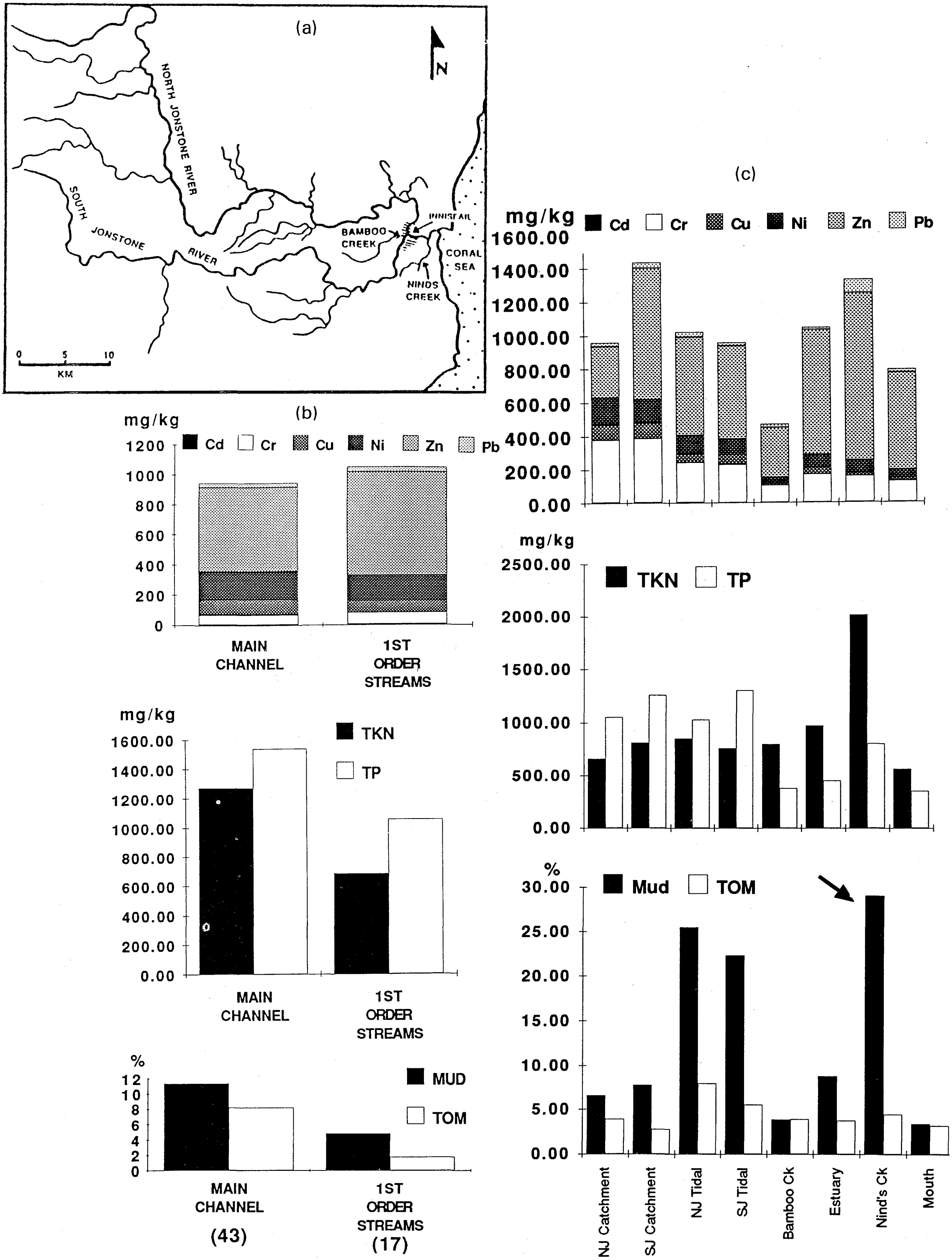

Fig. 2 (a) Regional map of the North Johnstone (NJ) and South Johnstone (SJ) Rivers; (b) cumulated concentration of trace metals, nutrients, mud, and total organic matter for bottom sediment samples collected during baseflow for the main channel and first-order streams; (c) cumulated concentration of trace metals, nutrients, mud content, and total organic matter in bottom sediment samples from the same sampling sites as (b) after major runoff. Arrow indicates point-source input to Ninds Creek from a sewerage treatment plant. Numbers in brackets denote number of samples in each group. Abbreviations are as used in Fig. 1.

increase in the basaltic mud component of sediment in streams discharging directly to the main channel (Arakel, 1995). As shown in Fig. 2(b), the cumulated concentration of sediment-bound metals in first-order channels of catchments, collected during base-flow, is generally within the ranges of the same metals in the estuarine reaches. In contrast, the cumulated concentration of trace metals in bottom sediment collected immediately after a major runoff event from the catchments is relatively high compared with cumulated concentration of the same metals in depositional zones of the main channel in downstream reaches (Fig. 2(c)). In both cases, the trace metal values relate to analyses performed on the mud fraction (<0.063 mm) of bed samples. Note that for the same samples, total phosphorous concentration was highest in downstream reaches of the river, regardless of time of sampling, lithology, and extent of fertilizer application (cf. Pailles *et al.*, 1993).

Nutrients

Determination of the extent of nutrient fluxes is critical for modeling nutrient cycling in the rivers and for predicting benthic productivity and community structure. Geochemical behavior of major nutrient species in bottom sediment of the rivers provides insight to the extent of spatial and temporal variability in bed sediment chemistry as a function of bottom dynamics and input sources. For the Johnstone Rivers (Fig. 2), total Kjeldahl nitrogen (TKN) concentration in bed sediment ranges from 789 mg kg^{-1} in Bamboo Creek (Fig. 2(a)), which is devoid of major point-source input, to 2009 mg kg^{-1} in Ninds Creek, which receives effluent from a municipal sewage treatment plant. Total nitrogen shows a moderately positive correlation ($r^2 = 0.65$) with mud content of bottom sediment. Spatial variability in the concentration of sediment-bound nutrients in the main channels of the South Johnstone and Hawkesbury-Nepean Rivers (Figs 1 and 2) is influenced by effluent input via second-order streams receiving point-source discharge. Thus, in estimating total loading of sediment-bound nutrients, the impacted creeks are considered discrete point sources for downstream estuarine reaches of the rivers.

Measurement of total phosphorus (TP) and TKN concentrations in core samples from Smalls Creek, an urban stream in the Hawkesbury-Nepean River basin (Fig. 3), indicate a potential for considerable assimilative capacity of fine sediment in pools of the stream. The sediment nutrient concentrations in these pools are several fold higher than nutrient concentrations in sediment samples from riffle zones connecting the pools. Similarly, elevated concentration of trace metals in the fine sediment of pools highlight the role of bottom sediment in assimilation of contaminants (Jones *et al.*, 1993).

DISCUSSION AND CONCLUSIONS

From the review presented above, it is evident that any strategy for establishing regional sediment quality assessment criteria for Australian river basins requires a high degree of flexibility and consistency; water quality criteria must aim to improve water quality and amenity value of waterways through reduction of point and nonpoint source impacts. Establishment of sediment quality criteria for a given aquatic system, however, requires the identification of "area-typical" values for key sediment quality determinants. This is

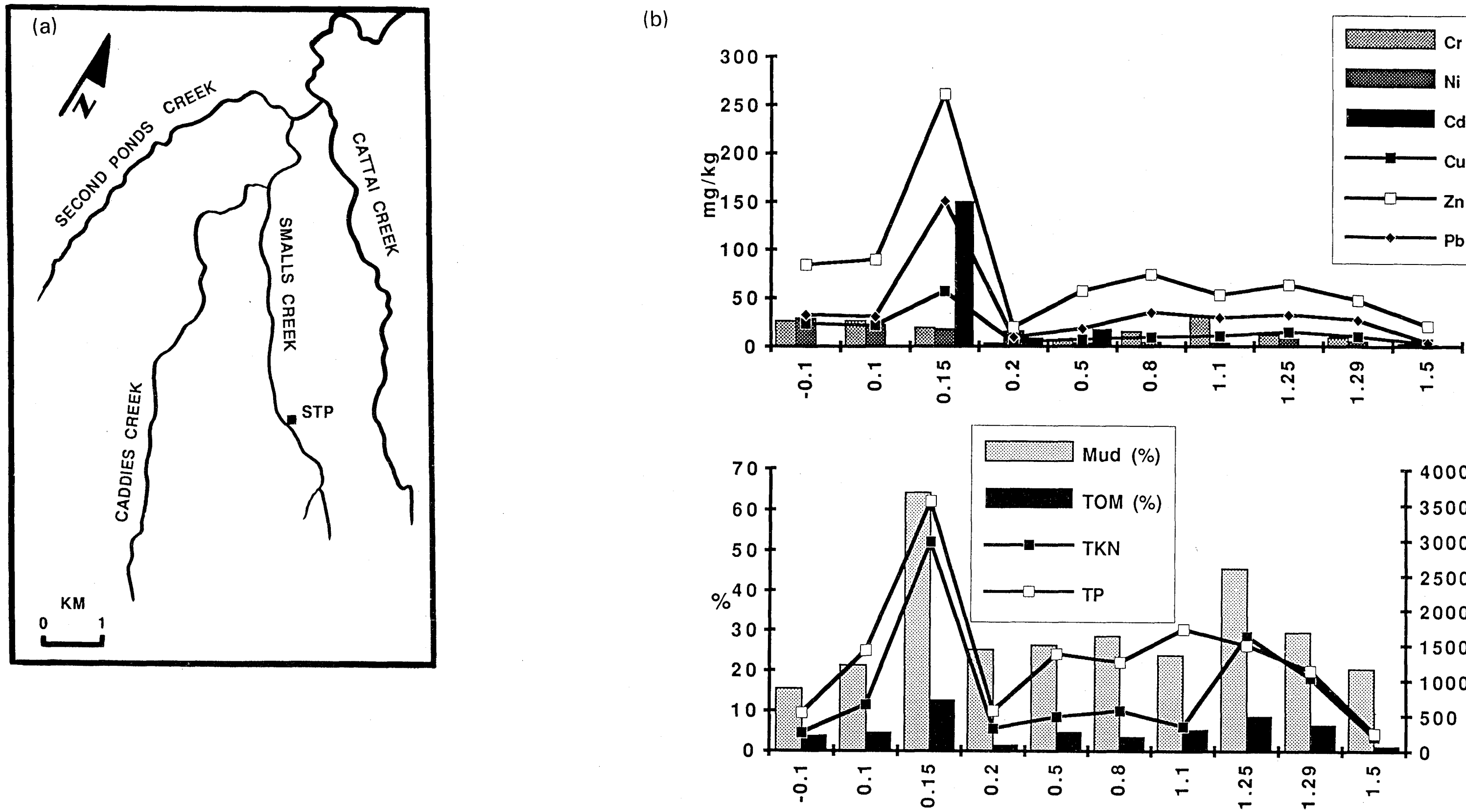

Fig. 3 Downstream variability in trace metal and nutrient concentrations, mud content, and total organic matter of bed samples from depositional pools in Smalls Creek, in mid-catchment of the Hawkesbury River basin. Distances shown are from an effluent discharge point.

achievable through a hierarchical assessment of regional variability in sediment quality, provided that the extent of textural variability and chemical status of bottom sediment in major depositional areas of a river basin, as discrete compartments of a drainage system, are first assessed. Information from these discrete but interconnected depositional areas then may be linked to provide an overall picture. The concept of "Sediment Effect Zone", shown schematically in Fig. 4 and detailed in Arakel (1995), provides a framework for such a systematic evaluation of sediment variability as a function of change in local and regional hydrological conditions and land use impact. Accordingly, this approach allows delineation and description of physical, chemical, biological, and anthropogenic features in sedimentation zones of a drainage network. Geochemical surveys undertaken at either or both local (depositional unit) or regional (depositional area) scales enable refinement of the scale of spatial variability in sediment characteristics. Information on the nature and extent of toxin exchange between sediment and water at local scale can be used to develop a regional context for comparative assessment of environmental impact by means of extrapolation and mathematical simulation.

The assessment of sediment quality, based on textural features of bed sediment and bottom dynamics in depositional zones, allows significant consistency for inter- and intra-basin assessment of contaminant sources and their dilution fields. The key outcome of the proposed hierarchical approach may be inventories on sediment quality consistent with local and regional hydrological settings, sedimentation history, and land use

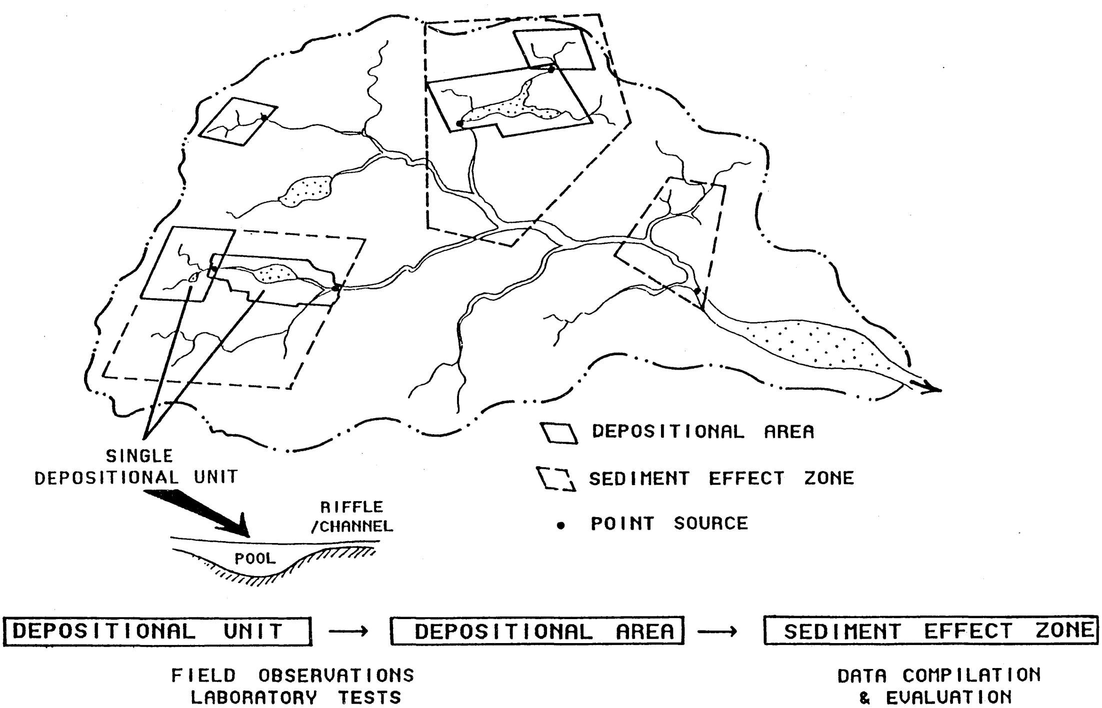

Fig. 4 Schematic representation of sediment deposition system in a drainage basin, and recommended approach to sediment quality assessment based on the concept of "Sediment Effect Zone" (Arakel, 1995).

characteristics. Resultant sediment inventories can be used to develop inventories of critical pools of contaminants and contaminated sites from which appropriate sediment quality standards and management options can be established. By using information on vertical variation in sedimentary textures and compositional features in dated sediment cores, consideration can be given to the time scale involved in changes to properties of aquatic sediment as a means for assessing potential for natural recovery of aquatic sediment on a regional scale.

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