APPLYING ENVIRONMENTAL MAGNETISM TO SEDIMENT TRACING

G. G. CAITCHEON
CSIRO Division of Water Resources, P.O. Box 1666, Canberra ACT 2601, Australia

ABSTRACT A new method for spatial tracing of sediment in fluvial environments has been developed. The method makes use of magnetic minerals that occur naturally in soils and sediments. Sediment transport mechanisms have an averaging effect that produces well-mixed magnetic mineral assemblages along river reaches. This results in constant magnetic parameter relations that are characteristic of the rocks and soils in the tributary catchment. At river junctions where two drainage basins deliver magnetically-distinguishable averaged sediment mixes, relative sediment contributions to the binary mix in the downstream reach can be determined. The method can be used to trace suspended and bed load sediments. Examples of the application of the environmental magnetism tracing method are provided.

INTRODUCTION

The question of where sediment is coming from in river basins is not only important from a water quality perspective, but also to studies of erosion and sediment delivery processes. Environmental tracers are being increasingly used to understand sediment delivery, without having to resort to detailed studies of the complex physical processes involved. Atmospherically-derived radionuclides, for example, are able to differentiate between surface and sub-surface soil sources (Walling & Woodward, 1992; Wallbrink & Murray, in press). Environmental magnetism has also been used to trace sediment derived from topsoils and subsoils (Walling et al., 1979; Dearing et al., 1986; Stott, 1986). Spatial tracing using mineral magnetism has been achieved by matching the magnetic fingerprints of catchment source materials with a sequence of accumulated sediment in a sink, such as a lake or estuary (Oldfield, et al., 1985; Yu & Oldfield, 1989; Dearing, 1992). However, this method is practically limited to catchments with suitable sinks and a relatively small number of source types to be magnetically fingerprinted.

A new method has been developed to measure the relative importance and spatial distribution of suspended and bed load sediment sources using magnetic minerals. It is based on the assumption that sediment transport mechanisms have an averaging effect as sediment is delivered to stream channels and then transported for some distance over some period of time. The characteristics of catchments (such as size) determine the rate of averaging of sediment mixtures in channels. Magnetic minerals in sediments also tend to be uniformly mixed, resulting in linear relations between environmental magnetism parameters. It has been empirically demonstrated that these relations, and therefore the assemblages of magnetic minerals from which the relations are derived, are spatially and temporally stable in the fluvial environments studied (Caitcheon, in press). Given that the tracing parameters have constant relations, they must also be able to distinguish between different sources.
Sediments from adjacent drainage basins that have different rock types usually produce distinctive magnetic parameter relations. At confluences, these magnetic signatures can be used to determine the relative sediment contribution of each basin. This is achieved by measuring the magnetic parameters of suspended or bed load sediments collected from the tributary and downstream reaches. The relative tributary contributions to the resultant binary mix in the downstream reach is then calculated from the magnetic parameter relations by a simple method. Using this approach, the principal source catchments can be ascertained by a progressive sequence of confluence measurements along a drainage network.

This paper presents examples of the application of the spatial mineral magnetic tracing method. The examples include suspended and bed load sediment tracing in a small catchment and in two large river basins.

METHOD

Representative sediment samples were collected from the tributary and downstream reaches at confluences. Bed load samples are normally made up of many subsamples collected from different bedforms along and across the channel. The length of reaches sampled varies from <1 to about 5 km, depending on the characteristics of the river or stream. Reaches downstream of confluences were sampled at distances estimated to be sufficient for total mixing of tributary sediments. Suspended sediment samples were obtained with a continuous flow centrifuge.

FIG. 1 Study site locations.
Bed load samples where wet sieved to obtain the silt-clay (<63 μm) and sand (63 μm - 2 mm) fractions. The sand fraction is normally split into sub-fractions because there is a tendency for heavy minerals (including magnetic minerals) to concentrate in fine sand (63-125 mm), resulting in different magnetic characteristics between sub-fractions. Suspended sediment samples were not sieved.

Samples were dried at <50°C. Low frequency (0.45 kHz) specific susceptibility (χ) was measured with a Bartington meter and MS2B sensor. Isothermal remanent magnetizations (IRMs) were imparted at 20 milli Tesla and 850 mT with a Molspin pulse magnetizer and the resulting magnetizations measured with a Molspin fluxgate magnetometer. Bivariate parameter relations (IRM850 vs. χ and IRM850-IRM20 vs. IRM20) are used to analyze the data. These parameters are regarded as being mutually independent and generally representative of magnetic mineral assemblages (see Caitcheon (in press) and Oldfield (1991) for a discussion of magnetic parameters).

SEDIMENT TRACING APPLICATIONS

In what follows, examples are given of how the spatial tracing method can be applied. The first example deals with a sediment sourcing problem in a large, remote catchment in the monsoonal tropics of Western Australia. Then a study of a coastal lagoon that has a 35 year history of sediment contamination is discussed. Finally, some preliminary results are presented from a suspended-sediment tracing study of one of Australia's largest rivers.

The Ord River

The Ord River catchment (46 000 km²) is in the monsoonal tropics of Western Australia (Fig. 1). Extensive erosion has occurred since the introduction of cattle grazing last century. In 1972 the Lake Argyle dam was constructed on the Ord River for irrigation water storage. The long term economic viability of the reservoir is now at risk from the accumulation of sediment. Due to the catchment's size and remoteness, available discharge and sediment data do not exist for sufficient tributary streams to source sediment reaching the reservoir. A pilot magnetic mineral tracing study was undertaken to measure the relative sediment contribution of the major tributaries. Representative bed sediment samples were collected at tributary junctions during the 1989 dry season. Results from the four major tributaries are presented below.

Magnetic measurements of the fine sand fraction (63-125 μm) are given in Fig. 2. In all of the examples the magnetic parameter linear relations distinguish the tributary sources. However, the IRM850-IRM20 vs. IRM20 linear regressions from the Nicholson and Osmond Rivers are nearly indistinguishable. In these cases, IRM850 vs. χ is used to determine relative tributary contributions.

The method used to estimate relative contributions is to standardize the parameters to be included in the analysis, and calculate principal components from the matrix of sums of squares and products about a common origin. The first two components normally account for 98% of the variance, so the second component can be regressed on the first and relative tributary contributions (C_r) calculated from the three regression coefficients using the following expression:

\[ C_r = \frac{x_{\text{tributary 1}} - x_{\text{downstream mix}}}{x_{\text{tributary 1}} - x_{\text{tributary 2}}} \times 100 \]
FIG. 2 Magnetic parameter relations from junctions of the Ord River with the (a) Panton, (b) Nicholson, (c) Osmond, and (d) Negri rivers.
Applying Environmental Magnetism to Sediment Tracing

<table>
<thead>
<tr>
<th>Tributary</th>
<th>Relative Contribution (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Panton</td>
<td>37 ± 10</td>
</tr>
<tr>
<td>Nicholson</td>
<td>0 ± 14</td>
</tr>
<tr>
<td>Osmond</td>
<td>60 ± 63</td>
</tr>
<tr>
<td>Negri</td>
<td>32 ± 7</td>
</tr>
</tbody>
</table>

The results given in Table 1 show that the Panton, Osmond, and Negri Rivers make significant contributions to the Ord River. However, there can be little confidence in the Osmond result given the large statistical uncertainty. In this case more data are required to define adequately the tributary and resultant mix relations. While these results are only the outcome of a single sampling exercise, and nothing is yet known about temporal variability, they give a quantitative indication of the relative importance of sub-catchments as sediment sources where no data previously existed. Re-sampling at confluences, as well as sampling of alluvial sequences, is being completed to provide an assessment of the temporal variability of sediment sources.

Lake Illawarra

Lake Illawarra is a coastal lagoon situated on the New South Wales coast 80 km south of Sydney (Fig. 1). A coal fired power station operated from 1955 to 1990 on the southwestern shore of the lake. As part of a lake sediment contamination study, mineral magnetic tracing was used to determine the relative contribution of fly ash to the lake’s sediment. In this situation it is assumed that the only sources of lake sediment are the catchment of Duck Creek (20 km²) that drains into the lake adjacent to the power station, and fly ash emissions from the power station itself. A 75 cm sediment core was obtained from the lake at the mouth of Duck Creek, approximately 1.5 km south of the power station. A density separation analysis of the >63 μm fraction showed that ash is present to a depth of 50 cm (Yassini, et al., 1991). This depth correlates with the commencement of power station operation in 1955. Bed sediment samples where collected along a 2.5 km reach of Duck Creek and a fly ash core was obtained from an ash disposal dam. All samples were sieved to recover the <63 μm fraction.

Magnetic data relating to the Duck Creek, lake core and ash dam sediments are given in Fig. 3. The interparametric relations clearly distinguish the Duck Creek and fly ash sources. Data from the lake core lie between the two sources, but, the closeness of the IRM₈₅₀ vs. χ relations means that there is considerably more uncertainty about relative source contributions than is the case for the IRM₈₅₀-IRM₂₀ vs. IRM₂₀ relations. The latter relation is therefore used to estimate the mean fly ash contribution, using the method outlined in the previous section, to be 10 ± 9% for the <63 μm sediment fraction. This is equivalent to 8 ± 8% of the total sediment. While the statistical uncertainty of this result is relatively high, the mean value is consistent with the density separation analysis of the >63 μm fraction. This showed 0.6% of the total sediment contains coarse ash particles which are normally a very minor component. Most fly ash is <10 μm.
The Murrumbidgee River

Magnetic mineral tracing is being used as part of a study to trace the sources of suspended sediment in the Murrumbidgee River. The reach of the river studied extends from the...
Burrinjuck Reservoir in New South Wales to the river's end at its confluence with the Murray River (Fig. 1), a distance of approximately 1150 river km. There is one major tributary, the Tumut River, 130 km downstream of the reservoir and a number of minor ones to about 400 km. Downstream of this point there are several irrigation water diversions. Suspended sediment samples were collected at 10 locations downstream of the Tumut River on 3 separate occasions through 1991-92. To obtain longer-term suspended sediment data, a 67 cm sediment core was obtained from a cut-off meander loop known as Hook Billabong, about 440 km downstream of Burrinjuck Reservoir. The billabong receives overbank flood flows with a return period of about 2 years. The first appearance of $^{137}$Cs in the core at 35 cm shows that suspended sediment has been accumulating from at least 1960 at a rate of approximately 1.1 cm year$^{-1}$.

The results show a high degree of consistency between the suspended sediment and core data (Fig. 4). This indicates that the source, or combination of suspended sediment sources, has remained relatively constant over a period of at least 30 years. As yet, insufficient data are available from the Tumut River, or Murrumbidgee River upstream of the Tumut confluence, to give a clear indication of the relative contribution of these sources. The role of several minor tributaries downstream of the confluence also cannot be ignored. The constancy of the suspended sediment's magnetic signature indicates that there could be a major source such as sediment from the Murrumbidgee floodplain. Minor tributaries, as well as the Murrumbidgee River channel, would therefore be important sources. Although at this stage the data are equivocal, they show that overbank deposits are a useful source of temporal data about sediment sources.

**CONCLUSION**

The advantages of the mineral magnetic tracing method are that sampling and analysis are relatively simple, and results are rapidly available. It works at any scale where two catchments deliver magnetically-distinguishable sediments to a confluence. The temporal variability of sediment sources can be monitored by re-sampling on a regular or event basis. Alluvial deposits downstream of confluences may also contain a record of long term changes in sediment sources. The method overcomes previous difficulties of measuring bed load delivery, at least in relative terms. Relative suspended sediment delivery can be measured, although, this is more difficult because transport rates are at least an order of magnitude greater than bed load, and source contributions may change rapidly during flood events. Sampling the proportion of suspended load combined with the bed load may offer a partial solution to this problem.

Sediment delivery is the product of many complex space and time dependent variables that change according to spatial and temporal scales. The spatial tracing method has the advantage that it cuts through much of the complexity by measuring the results of these processes at appropriate scales. Thus new opportunities exist to study processes associated with sediment delivery, including nutrient and contaminant sources, and the links between erosion and sedimentation.

**REFERENCES**


