TRACING THE SOURCE OF SEDIMENT IN AUSTRALIAN COASTAL CATCHMENTS

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INTRODUCTION

Many studies using tracers to quantify fluxes of sediment have been published over the last four decades. However, there is still insufficient information to enable routine selection of suitable tracers outside a limited number of study catchments (Foster *et al.*, 2000). There is increasing evidence to suggest that multiple tracers provide better discrimination than one tracer because no single tracer property can represent all the characteristics of a source (Caitcheon *et al*., 1994). This paper presents an application of geochemical sediment tracing in Australian coastal catchments. It shows the importance of considering multiple tracers and a practical approach to their use.

STUDY AREA

The Moruya-Deua and Tuross River catchments are located in the Eurobodalla area on the south east coast of New South Wales. The Moruya-Deua River drains a catchment of approximately 1480 km^2 and is fed by two large tributaries – Burra Creek and Araluen Creek. The Tuross River catchment is located south of the Moruya-Deua River catchment. It has a total area of approximately 2170 km^2. The main town in the Moruya-Deua River catchment is Moruya, with a smaller village at Araluen. Bodalla is the main town in the Tuross River catchment. On the coast near the mouths of the Moruya-Deua and Tuross Rivers are the townships of Moruya Heads and Tuross Head (Figure 1).
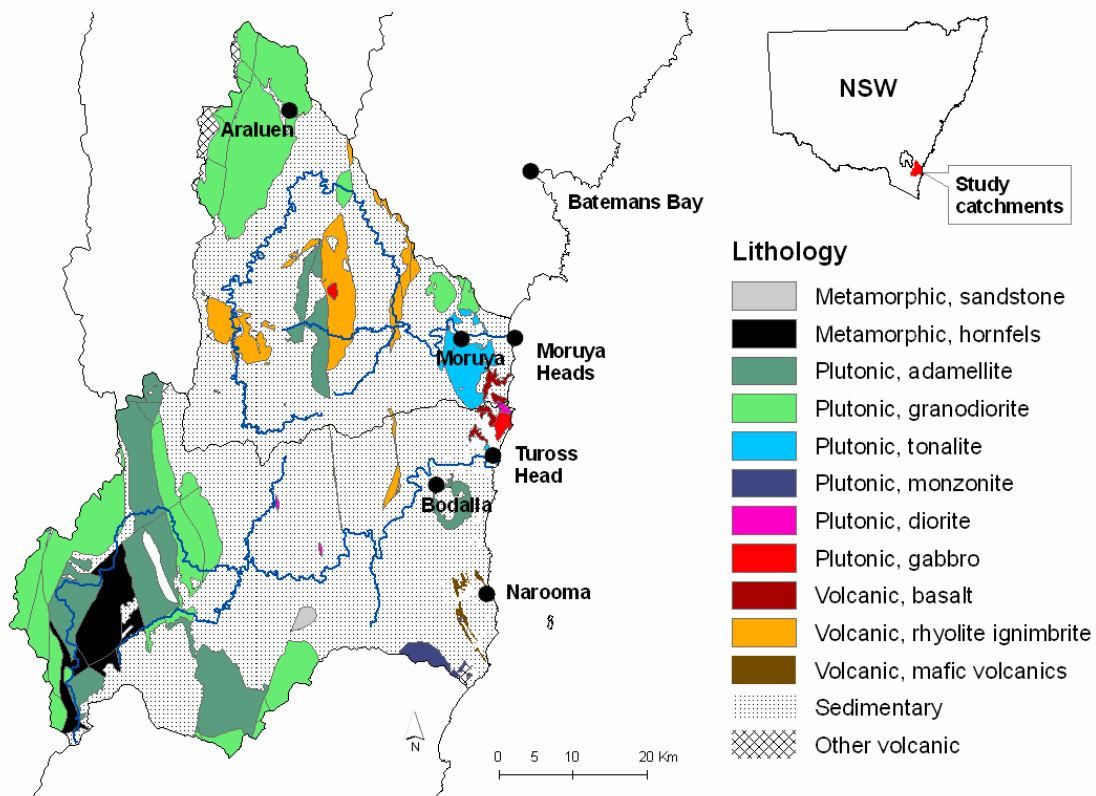

Figure 1: The location, localities and lithology of the Moruya-Deua and Tuross River catchments.

The Moruya-Deua and Tuross River catchments provide drinking water supplies for nearby towns including Batemans Bay, Moruya, Bodalla and Narooma. Therefore, water quality is of high concern. The ecological importance of maintaining good water quality in these catchments is also high due to the estuaries and marine habitats they support.

The majority of the Moruya-Deua and Tuross River catchments consist of early Ordovician metasedimentary rocks, covering about 43% and 45% of the catchments respectively. These comprise a turbiditic sequence of interbedded sandstone-mudstone-shale/slate (Lewis *et al*., 1994). Quartz is the dominant framework grain, with sublitharenites containing mica, plagioclase and K-feldspar (Lewis *et al*., 1994). The Ordovician metasediments usually underlie steep and forested land. The soils formed from them are typically gravelly Brown Soils and Massive Earths. Sedimentary rocks of younger age cover another 18% of the area in both catchments. Approximately 26% and 30% of the area in the Moruya-Deua and Tuross River catchments are underlain by plutonic rocks. The plutonic rocks, named the Bega Batholith, are dominated by moderately quartz-rich rocks composed of adamellite, granodiorite and tonalite (Lewis *et al*., 1994). Basalt is very limited in both catchments, with a scattered and disparate distribution pattern in coastal regions (Figure 1).

METHODS

This project applied several sediment budgeting techniques including sediment tracing and modelling to quantify sediment sources. This paper focuses on the application of a sediment tracing study in the Moruya-Deua and Tuross River catchments using geochemical tracing techniques.

Field sampling was carried out in February 2006. The samples were taken from sediments deposited in the active stream channel, predominantly from the top 0.5 centimetres. These sediments are usually trapped by vegetation in the stream channel. Five confluences were sampled, with two confluences (Junctions 7 and 8) in the Moruya-Deua River catchment and three (Junctions 9, 10 and 11) in the Tuross River catchment. The locations of the junctions are mapped in Figure 3. At each confluence two upstream sites ("A" and "B" in Figure 2) and one downstream site ("C" in Figure 2) were sampled. Four to six replicate samples were collected at each site.

In the laboratory, each sample was washed through 2000 μm, 1000 μm, 500 μm, 250 μm, 150 μm, and 63 μm sieves with deionised water. The < 63 μm fraction of sediment was air dried and treated with 30% hydrogen peroxide to remove organic matter. The treated samples were then analysed with ICP-AES following acid digestion with 15 mL nitric acid and 5 mL of perchloric acid. The elements analysed are listed in Table 1.
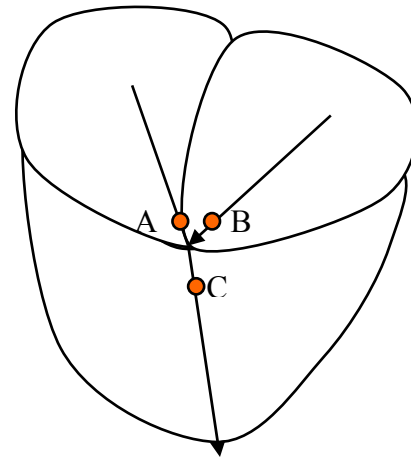

Figure 2: Diagram showing site locations at a hypothetical stream confluence. In practice, sites "A" and "B" are located approximately 1 km upstream of site "C".

Table 1: Analysed elements using ICP-AES

Element class	Analysed elements
Major elements	Al, Ca, Fe, K, Mg, Na, Ti
Trace elements	Ba, Co, Cu, Ga, Mn, Mo, V, Zn
Rare earth elements	Ce, Gd, Nd, Pr

The multivariate sediment-mixing model of Collins *et al*. (1998) was simplified for use in this study. The model estimates the optimal contributions from individual sources by minimizing the sum of squares of the weighted relative errors (Collins *et al*., 1998). In this study, the particle size correction factor and organic matter content correction factor were removed from the model, because both sources and mixture were analysed for the same particle size fraction (< 63μm); and organic matter was removed from all samples using hydrogen peroxide before analysing the element concentrations. The tracer-specific weighting was not taken into account because there were no data for replicate analysis for the laboratory measurement. The median concentrations of tracer parameters in sources and mixture were used instead of the mean, due to the high variance of the concentrations. Consequently, the simplified multivariate mixing model is:

$$\text{Minimizing} \sum_{i=1}^{n} \left(\frac{\overline{[C]}_i - [E]_i}{\overline{[C]}_i} \right)^2$$

Where $[E]_i = \overline{[A]}_i * x + \overline{[B]}_i * y$

Constrained by: $x + y = 1$, and $0 \le x \le 1$.

$[E]_i$ = estimated concentration of tracer parameter (i) in mixture samples;

$\overline{[C]}_i$ = median concentration of tracer parameter (i) in mixture samples;

$\overline{[A]}_i$ = median concentration of tracer parameter (i) in tributary "A" samples;

$\overline{[B]}_i$ = median concentration of tracer parameter (i) in tributary "B" samples.

x = percentage contribution from tributary "A";
y = percentage contribution from tributary "B";

RESULTS

The tracers at each junction were selected based on two criteria:

C1) the median of the confluence downstream "C" value is between the median of the two upstream tributaries "A" and "B";

C2) the values of "A" and "B" are significantly different with 95% confidence.

Using the Wilcoxon rank-sum test, thirteen, ten, nine, and five element concentrations were significantly different at the 0.05 level for source tributaries of Junctions 7, 8, 10 and 11, respectively (Table 2). There was no tracer that detected the proportional contribution of Junction 9 because all the concentrations of elements examined in mixture "C" were higher than those from tributaries "A" and "B". Based on the above criteria, elements that are marked both "C1" and "C2" in Table 2 were selected as tracers for proportional analysis.

Table 2: Tracer selection based on two criteria. "C1" means Criterion 1 is satisfied, while "C2" means Criterion 2 is satisfied. The two criteria are explained in the text. The elements in bold are used as tracers in one or more junctions.

Elements	Junction 7	Junction 8	Junction 9	Junction 10	Junction 11
Al	C2	C1		C1	
Ba		C1	C2	**C1, C2**	
Ca	C2	**C1, C2**	C2	**C1, C2**	C2
Ce	**C1, C2**	**C1, C2**	C2		**C1, C2**
Cu	C2			**C1, C2**	
Fe	C2	**C1, C2**		C1	
Ga	C2	**C1, C2**		C2	C1
Gd	**C1, C2**				**C1, C2**
K					
Mg		C2			
Mn	C2	**C1, C2**	C2	**C1, C2**	
Na		**C1, C2**			C1
Nd	**C1, C2**	**C1, C2**	C2	C2	**C1, C2**
Pr	**C1, C2**		C2		C2
Ti	C2	**C1, C2**	C2	**C1, C2**	
V	C2	**C1, C2**		**C1, C2**	C1
Zn	C2	C1		**C1, C2**	

The multivariate mixing model was run using the Solver program in Microsoft Excel® using the generalized reduced gradient optimisation method. To calculate the errors associated with the mixing model, the actual tracer concentrations measured from the mixture "C" samples ($[C]_i$) were compared with the concentration calculated from the estimated mixture ($[E]_i$) (Collins *et al.*, 1998). The percentage contribution from tributary "A" estimated from the model, and the mean percentage error are listed in Table 3.

Table 3: Estimated proportional contributions of sediments from tributary "A" and mean percentage error.

Junction	Confluence name (A-B)	A% by model	Mean percentage error
7	Burra Ck – Donalds Ck	30.09	7.36
8	Moruya-Deua R – Burra Ck	45.18	11.33
9	Tuross R – Reedy Ck	NA	NA
10	Tuross R – Wadbilliga R	54.30	28.37
11	Tuross R – Belimbla Ck	83.95	3.25

Given that the distances between Junctions 7 and 8, and Junctions 10 and 11 are short, the percentage contributions of each pair of confluences were combined. The percentage contributions of the subcatchments were then normalised by their drained subcatchment areas. The results show that in the Moruya-Deua River catchment, the Donalds Creek subcatchment contributes a higher proportion of sediment per unit area to

Point M (Figure 3). In the Tuross River catchment, the three subcatchments in the upper reach of the Tuross River have similar proportional contributions per unit area. The Wadbilliga River subcatchment contributes a slightly higher percentage of sediment per unit area. The results highlight the hotspot subcatchments in terms of sediment control management. Investment in sediment control in these two subcatchments could be more effective than a comparable investment in other areas.
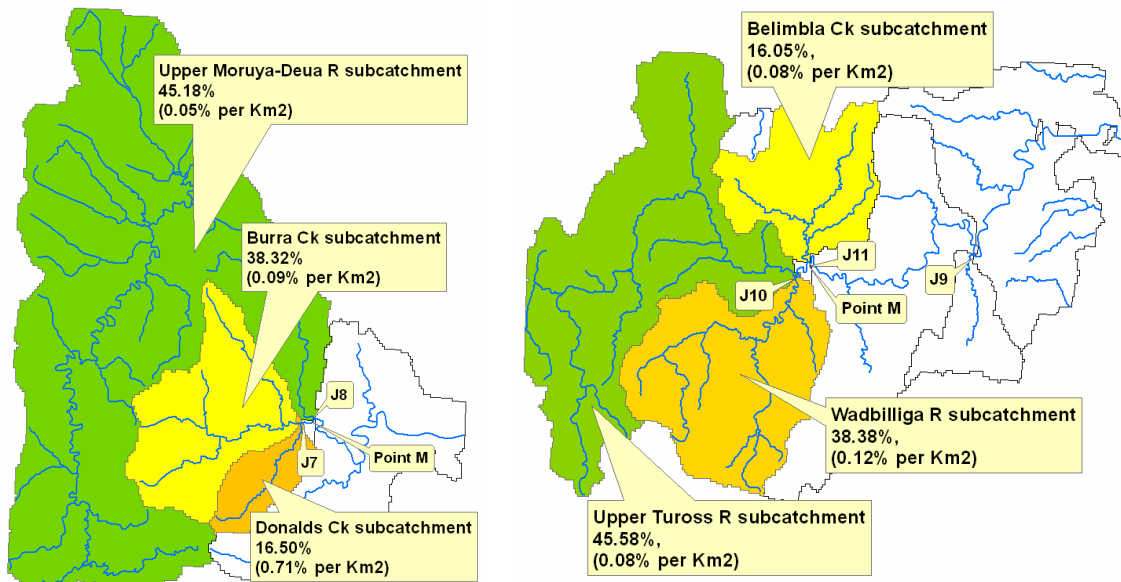

Figure 3: Percentage contribution and percentage contribution per km^2 of subcatchments in the Moruya-Deua (left) and Tuross (right) River catchments. The locations of the junctions and Point M (see text) are also mapped.

DISCUSSION

The use of a multivariate mixing model does not take into account the differences between individual tracers. In most literature using a multivariate mixing model, tracers are only selected based on significant differences between the sources. Whether the mixture is outside the range of the sources was not considered. In this paper, the model was run based on different tracer combinations for Junction 7 (Table 4). For Junction 7, the elements that satisfy the mixture median concentrations within the range of sources are: Ce, Gd, Nd, and Pr. The elements that show significant differences between sources are: Ce, Gd, Nd, Pr and Al, Ca, Cu, Fe, Ga, Mn, Ti, V, and Zn. Tracer selection is critical in estimating the proportional contribution. The presence of Mn can significantly increase the proportion of sediments from tributary "A", and hence alter the critical sediment sources (Table 4). Other sensitive tracers are Ti and Ga which increase the A% by 23 to 30%, and Cu and Zn which decrease the A% by 30%. These differences may be explained by chemical changes in deposited sediments, after deposition but before sampling. For example, Mn may be oxidized and precipitate by biochemical changes in the sediments. Changes in organic chelates and pH can cause adsorption or desorption of Cu on clay minerals (Wedepohl, 1972).

Walling *et al.* (1993) suggest that composite tracers should be used to avoid inconclusive discrimination of sources. However, this study shows that inclusion of different combinations of geochemical tracers may produce significantly different results. Therefore, unless all the tracers are tested, the results may be biased by the tracers that are selected. Different tracers selected for testing and those selected to be included in modelling may alter the outcomes. Any sediment tracing study should justify its geochemical tracer selection and the sensitivity of the tracers included in the model.

Table 4: Proportional contribution estimated from model based on different tracers for Junction 7.

Scenario	Selection criteria		Tracers	A % by model
	Mixture within range	Significant different sources		
1	Yes	Yes	Ce, Gd, Nd, Pr	30.09
2	Partial	Yes	Scenario 1 + Al	34.57
3	Partial	Yes	Scenario 1 + Ca	24.53
4	Partial	Yes	Scenario 1 + Cu	0
5	Partial	Yes	Scenario 1 + Fe	26.95
6	Partial	Yes	Scenario 1 + Ga	53.40
7	Partial	Yes	Scenario 1 + Mn	100
8	Partial	Yes	Scenario 1 + Ti	60.15
9	Partial	Yes	Scenario 1 + V	34.11
10	Partial	Yes	Scenario 1 + Zn	0
11	No	Yes	Scenario 1 + Al, Ca, Cu, Fe, Ga, Mn, Ti, V, Zn	75.77

In this study, high variances of element concentrations were found for most junctions. Some element concentrations from the combined mixture "C" were outside the range of tributaries "A" and "B". This may be due to the definition of the particle size fraction, failure to capture major sediment inputs and / or contamination of the samples. The particle size fraction may be too broad for geochemical analysis because the geochemistry for clay is usually different to silt. One option for future research may be to reduce the particle size fraction for analysis to < 10 μm. This may reduce the representation of tracers. Hence, other types of tracers, such as radionuclides and magnetism properties may be used in future analysis. Major sediment inputs between the sample sites of two upper tributaries and the combined mixture may have been missed, causing the mixture "C" to be outside the range of tributaries "A" and "B". Field inspection at these junctions is needed. The collected samples may have been contaminated by cattle or other animals. Only carbon was removed in the hydrogen peroxide treatment. Other elements from the organic matter remained in the samples. Sampling suspended sediment in the river flow may reduce the problem of collecting contaminated samples. Time-integrated and rising-stage samplers have been placed in the Moruya-Deua and Tuross River catchments to collect suspended sediment during storm events. Future research will analyse data collected from these samplers to quantify sediment sources.

CONCLUSION

This study used geochemical tracers to quantify sediment sources in the Moruya-Deua and Tuross River catchments at a proportional level. The results suggest that the Donalds Creek subcatchment in the Moruya-Deua River catchment, and the Wadbilliga River subcatchment in the Tuross River catchment contribute higher percentages of sediment per unit area than other subcatchments. Investment of money for sediment control in these two subcatchments could be more effective than investment in other areas. The simplified multivariate mixing model using different combinations of tracers for Junction 7 showed that different combinations of geochemical tracers may alter the outcomes. Using in-stream sediment samplers and different types of tracers such as radionuclides and magnetism properties is suggested for future research.

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