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SPARROW regional regression for sediment yields in New Zealand rivers

A. H. ELLIOTT[1], U. SHANKAR[2], D. M. HICKS[2], R. A. WOODS[2] & J. R. DYMOND[3]

1 *National Institute of Water and Atmospheric Research (NIWA), PO Box 11115, Hamilton, New Zealand*
s.elliott@niwa.co.nz

2 *National Institute of Water and Atmospheric Research (NIWA), PO Box 8602, Christchurch, New Zealand*

3 *Landcare Research, Private Bag 11052, Palmerston North 4442, New Zealand*

Abstract This paper reports on the application of the SPARROW regression model for predicting mean annual sediment yield in streams throughout New Zealand. SPARROW generates sediment (or nutrient) sources as a function of subcatchment parameters such as areas of different erosion terrains, modifies the loads according to generation and land-to-water delivery factors, and routes the sediment down a dendritic stream network, allowing for stream and lake erosion or deposition. The parameters for the model are determined by nonlinear calibration to measured yields at stream monitoring stations (over 220 sites in New Zealand). Areas of different erosion terrains were the key source in the model, while the mean annual rainfall and slope were key source modifiers. Land cover also emerged as a significant source modifier. A model with these terms gave a regression R^2 of 0.925 to the measured yields, in log space. Stream erosion and deposition terms were not statistically significant, so they would have to be imposed rather than calibrated to stream yield data.

Key words regression; model; stream; SPARROW

INTRODUCTION

Prediction of sediment loads in streams and rivers is of interest in relation to sediment accretion in reservoirs and estuaries, sediment-related nutrient loads, and sediment stresses on freshwater biota. In many streams, there are no sediment gaugings so some sort of model is required for load prediction. This is particularly the case in New Zealand, where there is a wide range of sediment yields (Hicks *et al.*, 1996). Physically-based models typically require considerable effort to set up and run, and often calibration is required to reduce prediction uncertainty. An alternative approach is more empirically-based regression models, which relate stream loads to characteristics of the catchment and stream (e.g. Onstad, 1984).

Previously, a simple regression model was developed for prediction of sediment load in New Zealand (Hicks *et al.*, 1996; Hicks & Shankar, 2003). The regression gives the exported specific sediment yield as a function of erosion terrain class and rainfall, with complete trapping in large lakes and delivery implicit within the sediment yield coefficients. The results are presented as a grid map of specific sediment yields. Recently, the SPARROW model (Spatially Referenced Regression on Watershed attributes, Smith *et al.*, 1997; Schwarz *et al.*, 2006) has been used to predict mean annual nutrient loads in New Zealand (Elliott *et al.*, 2005). This hybrid mechanistic-regression model incorporates a mass budgeting approach, whereby mass is generated in source areas and routed down the stream network, accounting for loss processes in the network. The budgeting approach is used in an effort to improve the physical interpretability of model parameters, and to obtain a clearer picture of the main influences on mass generation and delivery. A nonlinear optimisation method is used for parameter estimation, rather than the linear or log-linear regression used in traditional sediment regression modelling. Schwarz *et al.* (2005) applied SPARROW to suspended sediment loads in the USA, and found that stream erosion (bank and bed erosion) was an important source, along with areal sources differentiated by land use and modified by vegetative cover, rainfall erosivity, slope, and soil permeability. John Brakebill (USGS, personal communication, 2007) has applied SPARROW to sediment in the Chesapeake Bay area, and found that stream erosion, urban development, and area of land use were key source terms, with modifications for geology, slope, areal density of reservoirs, soil permeability and drainage density. In lower reaches of the stream system, deposition in the streams was also important.

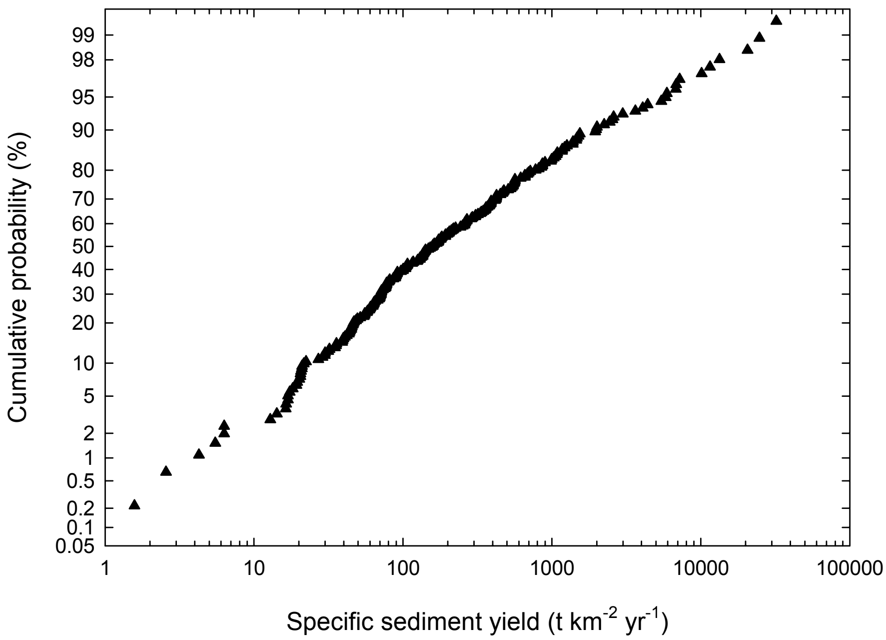

Fig. 1 Distribution of specific sediment yields for the monitoring sites used for model calibration. The vertical axis is a normal distribution scale.

In this paper, we present the application of SPARROW to suspended sediment yields in New Zealand. This extends the previous sediment regression modelling by attempting to incorporate more source terms and stream delivery or transport processes, and by using a different regression method. The New Zealand application is of interest as it includes a wide range of sediment yields (Fig. 1), rainfall rates and geological settings.

METHODS

A detailed description of SPARROW is provided by Schwarz *et al.* (2006). Here, we provide a brief overview of the model, and describe the application of the model to sediment for this study. In SPARROW, the region of interest is broken into a number of subcatchments, each of which feeds to a reach in a dendritic drainage network. In each subcatchment, there may be a number of sources. Each source has an associated source coefficient, such as an area-specific erosion coefficient. The sources may be modified according to attributes of the subcatchments such as slope or rainfall. In the original SPARROW terminology, these modification terms are called land-to-water delivery terms, but here we refer to them as source modification terms to avoid confusion with conventional use of the word "delivery" in erosion modelling. The modified sources are then accumulated down the drainage network, accounting for attenuation along the way. Attenuation may occur in reservoirs or lakes, or as losses in the stream network (typically characterised as a first-order loss function of reach length or travel time). There is some flexibility in the way in which the source, modification, and attenuation terms are specified. The various parameters in the model are determined by nonlinear gradient search optimisation methods within the SAS statistical package, to minimise the sum of squares of residuals between measured and predicted mean annual sediment fluxes (mass per year). The optimisation also provides parameter uncertainty estimates; in this application the uncertainty estimates for the final model were obtained with bootstrap methods rather than local linear parametric approximation.

The candidate source, modification, and attenuation terms for the current study are summarised in Table 1, along with information on the related data sources. The New Zealand River Environment Classification drainage network was used (Snelder *et al.*, 2004). This network

Table 1 Candidate source terms.

Term	Description	Form for the term	Data sources
Source terms			
Area of erosion terrains	An erosion terrain represents a combination of surface geology type, landform or slope class, and dominant erosion process.	$c_e A_e$, where c_e is erosion coefficient, A_e is area of erosion terrain	Landcare Research, based on Land Resources Inventory (LRI, Newsome *et al.*, 2000) and Land Use Capability (LUC)
Stream erosion	Stream length in combination with modification terms (see below) gives erosion over the reach.	$c_b L$, where c_b is erosion coefficient, L is reach length	REC drainage network (Snelder *et al.*, 2004).
Source modification			
Land cover (for geology or erosion terrain sources)	Trees (pine plantation, native forest, scrub) as "base" land cover. Other land uses modify the source in a linear fashion.	$1 + \Sigma_j c_j f_j$, where f_j is fraction of land cover j in the subcatchment. c_j are coefficients (>–1).	Land Cover Database (LCDB2), based on satellite imagery (Terralink Intenational)
Mean annual rainfall (for areal source terms)	Power function of rainfall for the subcatchment	P^{α}, where P is mean annual rainfall, α is calibrated exponent	Rainfall normals (Tomlinson, 1994)
Slope (for areal source terms)	Mean slope of the catchment	S^{β}, where S is the mean subcatchment slope (degrees), β is calibrated exponent	30 m grid DEM derived from 20 m contours (Snelder *et al.*, 2004)
Soil drainage class (for areal source terms)	Ordinal class	$\exp(k_d D)$, where D is drainage class (higher number for better drainage)	LRI
Bankfull flow and slope (for stream erosion term)	Power function of mean annual flood flow and slope	$Q_{MAF}{}^{b} S^{d}$, where b and d are calibrated parameters, Q_{MAF} is the mean annual flood flow and S is the reach slope.	S from the REC drainage network. Q_{MAF} from McKerchar & Pearson (1989)
Fraction riparian cover		$\exp(-k_r f_r)$, where f_r is the fraction of riparian cover, k_r is a coefficient	Riparian cover from overlay of LCDB with 100 m buffer of streams
Stream/lake attenuation			
Deposition	First order loss	Fraction settled in reach ~ $1 - \exp(-kQ^{f}_{bf}L)$, where k and f are calibrated parameters	As above
Reservoir/lake settling	Well-mixed settling basin	Fraction settled = $1/(1 + k_s Q / A_l)$ where A_l is the plan area of the reservoir, Q is the flow out of the reservoir, and k_s is an effective settling velocity	A_l from 1:50 000 topographic data, Q from Woods *et al.* (2006a)

contains approx. 560 000 reaches and associated subcatchments with a mean subcatchment area of approx. 0.5 km^2. Point sources were not included as a candidate source term, as they are expected to make a negligible contribution to the sediment yield.

The calibration data set was developed based on a database of mean annual suspended loads from 214 sites around New Zealand (Hicks *et al.*, 2003). The loads from each site were determined from rating-curve methods. The data cover various time periods in the last 50 years. If a site had a large part of the estimated sediment load associated with flows larger than those for which sediment gaugings were available, the site was dropped from the calibration data set.

The form for the bank erosion term (Table 1) was established as follows. Empirical relations for meander migration rate, M (m/year), take the form $M \sim (Q_{bf}S^{\alpha})^{\beta}$, where Q_{bf} is the mean annual flood flow, α is a coefficient, and S is the stream slope (deRose *et al.*, 2005). If a stream power approach is used, then α = 1; otherwise α = 0. The source of sediment, M_b (kg/year), for a reach of length, L, and with bank height, B, is $M_b \sim MLB$. Further, using a hydraulic geometry relation of the form $B \sim Q_{bf}^{\gamma}$, we obtain the form $M_b \sim L\, Q_{bf}^{b} S^{d}$. We did not account for the fraction of stream length with erodible streambank geology (for example, flood-plain deposits), nor for bank erosion varying with geological setting.

The in-stream deposition term is based loosely on the concepts in the SedNet model (Wilkinson *et al.*, 2004), whereby there is deposition in overbank flows with a single setting velocity and plug flow. For the preliminary assessment in this study, we did not account for the width of the flood plain in the deposition term.

The SPARROW standard form for source modification terms is exp(–kD), where k is a delivery coefficient and D is a delivery variable. To get a power function form of the delivery terms, log-transformed delivery variables were used.

RESULTS AND DISCUSSION

The coefficients for the final model form are shown in Table 2. This model provided an R^2 of 0.925 in log-transformed space. The root mean square error was 0.80 in natural log space, or a factor of 2.2. Predicted and measured values are compared in Fig. 2. In the fitting process, one source (Waiau at E309 Ford, on the Coromandel Peninsular) was removed, as its sediment rating curve was of poor quality and the specific yield was greatly different from sites with similar geology in the same

Table 2 Model coefficients in the final model.

Coefficient	Value (median)	10% CI	90% CI
Areal sources, b_e (t km^{-2} year^{-1})			
Sand country, flood plains, fans and terraces, peat	51.1	20.3	84.9
Tephra and Loess	19.4	13.7	24.5
Tertiary mudstone, sandstone, soft limestone	190	133	266
Crushed sedimentaries and metasedimentaries	80.6	0.001	319
Intensely gullied crushed argillites and greywacke	10 300	6 800	15 300
Lavas, rhyolite, volcano slopes	18.5	5.99	40.8
Greywacke, argillite, hard limestone	41.4	24.5	53.8
Schist and South Island greywacke	53.7	34.7	82.6
Coarse crystalline plutonics and metamorphics	0.821	0.001	6.5
Deeply weathered plutonics	581	188	1 300
Other	30.4	2.42	130
Source modification terms			
Rain exponent, α (dimensionless) Rain in m year^{-1}	2.02	1.76	2.32
Slope exponent β (slope in percent)[b]	1.15	0.89	1.35
Pasture cover modification coefficient, c_p (dimensionless)	3.56	2.37	5.74
Tussock and high country cover modification coefficient, c_t	–0.27	–0.80	0.43
Other non-tree cover modification coefficient, c_o	1.19	–0.37	3.33
Attenuation terms			
Lake effective settling velocity (m/year)	200	–[c]	–
Root mean square error of yields (natural log space)	0.80		
Adjusted R^2 of yields	0.925		
R^2 of specific yields	0.793		

Note: [a] Rainfall values are divided by 1.56 m, to normalise values. [b] Slopes are divided by 17.6% , to normalise values. [c] Value fixed.

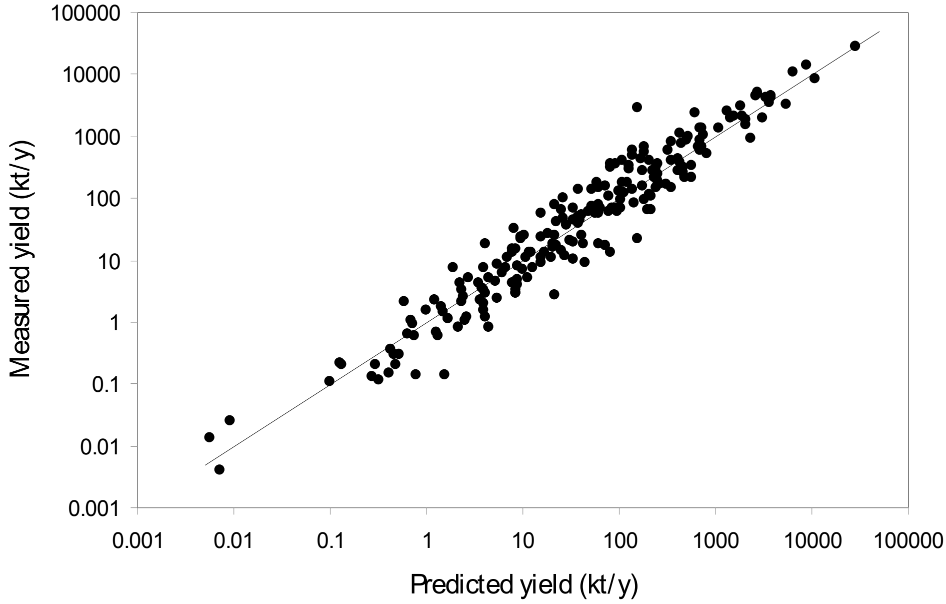

Fig. 2 Predicted *vs* observed sediment yields. The line is a 1:1 curve.

region. The remaining outlier (Pohangina at Mais Reach, in the Ruahine Ranges) was under-predicted by a factor of 4.5 and the load was measured in the 1960s, but the site was retained as there were no obvious data errors and the site was not influential on the model parameters. The remaining residuals followed a log-normal distribution, and showed no bias with location or measured yield.

The areas of various erosion terrains were the key source terms in the model. This confirms the finding by Hicks *et al.* (1996) that surface geology is a key driver of erosion. In exploratory simulations, we investigated surface geology classes rather than erosion terrains, and found that erosion terrains provided a slightly better explanatory power. This is in keeping with more recent work by Hicks & Shankar (2003). One of the main differences between the geology and erosion terrains is the inclusion of slope information in the definition of terrains, but this was not a key factor for the improvement of explanatory power associated with the use of terrain. This is partly because slope is included as a source modification term. More likely, the improvement was due to some relatively subtle aspects of the terrain classification, such as differentiating intensely crushed and gullied greywacke and argillite areas from other greywacke and argillite areas.

We also conducted exploratory simulations in which land uses were the key areas source terms, but this provided a much lower explanatory power. This finding contrasts with SPARROW modelling in the USA (Schwarz *et al.*, 2005), where the sources were discriminated on the basis of land use.

A considerable degree of aggregation of the erosion terrains was required to obtain sufficiently well-defined erosion coefficients. There were initially 96 terrains, and only 214 monitoring sites, so clearly there is not enough information to define the erosion coefficient for each of these terrains. An initial aggregation was therefore made based on combining similar terrains, moving up the terrain classification hierarchy, and lumping similar landforms, to bring the number down to 26. Even so, many of the erosion coefficients were poorly-defined. The number was further reduced by introducing a slope term and combining terrains in a wider range of slope classes. Most of the remaining poorly-defined classes were combined with similar terrains, based on expert assessment. This left 11 classes, as shown in Table 1.

The largest erosion coefficient was for intensely gullied and crushed greywacke/argillite, which is not surprising as these terrains are primarily in the East Cape region, which is notorious for the high erosion rates (Hicks *et al.*, 2000). The small coefficient for tephra is somewhat surprising given that soil conservation measures were introduced in the Central Volcanic Plateau. Possibly gross erosion in these areas has been stablilised. The smallest erosion coefficient was for coarse crystalline plutonics and metamorphics. The specific yield in catchments associated with these terrains is not as small as indicated by the erosion coefficient, because other relatively minor terrains make a significant contribution to the load.

Stream erosion was not retained in the final model. When it was included during exploratory model runs, stream erosion made a considerable contribution to the load (it typically halved the areal source coefficients). However, the coefficient has high uncertainty, and the 80% confidence interval included zero. This applied even when the stream slope, flow rate and riparian cover were included as source modification terms and when a first order flow-dependent stream loss term was included. In contrast, stream erosion was a significant source in SPARROW sediment applications in the USA (Schwarz *et al.*, 2005). It may be that in New Zealand, stream erosion is matched by deposition, over the time scales of the monitoring observations. The interaction between the stream erosion and source terms highlights the difficulties when attempting to resolve these two sources based on monitored loads at the catchment outlet. Possibly a better-defined coefficient might be obtained if the riparian geology (such as the presence of an alluvial flood plain) were taken into account, but this was not attempted in this study.

First-order stream deposition was not a significant term. This contrasts with experience in Australia and elsewhere (e.g. Prosser *et al.*, 2001), where the catchment-average specific sediment yield reduces with the catchment size (typically represented as a sediment delivery ratio or deposition process).

Rainfall was an important modifier of the sediment sources, as found earlier by Hicks *et al.* (1996). The exponent of 2.02 is comparable to that used previously by Hicks *et al.* (2004). Hence, a variation from 1 m of rainfall to 10 m induces a 100-fold increase in erosion rate. We calculated USLE mean annual runoff-erosivity values (R) for 183 climate stations according to methods in Henderson (1983) and Daly & Taylor (2002), and found that the these correlated with mean annual rainfall (P), with a power function relation $R \sim P^{2.01}$. Hence the exponent of 2.02 in the SPARROW model indicates that erosion increases with R, which is consistent with the USLE erosion equation.

The exponent in the slope source modification term had a value significantly different from zero. Removing the slope term marginally degraded the model performance (R^2 reduced from 0.925 to 0.916), even when the terrains were split into more slope classes. Hicks & Shankar (2003) did not use a slope term, arguing that slope and rainfall are correlated so that it was difficult to determine an effect of slope (Hicks *et al.*, 1996). Indeed, there is a correlation between the rain and slope exponents (–0.58, based on linear characteristics of the response surface), so that removing the slope term is compensated for by increasing the rain exponent to 2.6. This value is a little higher than the value of 2.3 used in Hicks & Shankar (2003).

Land cover was a significant modifier of erosion. The coefficient for pasture is 3.56, so that pasture has 4.56 times the erosion compared with the base land cover class of trees or scrub. This is consistent with the general observed effect of pasture on sediment yields in paired catchment studies (e.g. Quinn & Stroud, 2002). However, there is moderate uncertainty in this parameter. Moreover, a blanket value is used for all the country, whereas we might expect that the effect of pasture would vary with erosion terrain and geological setting. There is unlikely to be sufficient data to refine the effect of pasture further based on the monitored yields. Tussock had a coefficient of –0.27 with 80 percentile confidence interval, including zero but not the pasture coefficient. This result suggests that the yield from tussock areas is comparable to that from trees and scrub, but there are no suitable paired catchment studies to confirm this. Forcing a coefficient of zero had a minimal effect on the rest of the model coefficients. The “other” land-cover class includes urban areas and horticultural areas, but the coefficient is poorly defined. As expected, the pasture cover coefficient is negatively correlated with the erosion source coefficients. More surprisingly, the inclusion of the pasture term induced a positive correlation between some erosion coefficients, but the reason for this is unclear.

The reservoir/lake effective settling velocity had large variability in exploratory models. This is because there are no sites with a dominant lake influence in the calibration data set. Nevertheless, lakes are expected to have a strong influence on sediment loads. Therefore we assigned an effective settling velocity of 200 m/year, consistent with other SPARROW sediment modelling in the Chesapeake Bay area (John Brakebill, USGS, personal communication). There is little other guidance in the literature on effective sedimentation velocities. Popular empirical relations for sediment trapping efficiency (Verstraeten & Poesen, 2000) include reservoir detention time, but we do not have data on residence times for all New Zealand lakes.

There are some limitations with the SPARROW methodology as applied in this study. As noted previously, there are some poorly-defined erosion coefficients, which points to the need for targeted data collection in some geologies. The use of a single representative slope within a subcatchment introduces imprecision, because the correlation between erosion terrains and slopes within a subcatchment is not accounted for. For example, within a subcatchment the alluvial areas will have small slopes while upper steeper parts of the catchment may have a different geology. This correlation cannot be incorporated easily within the SPARROW framework. There are some fairly complex methods to deal with this (Schwarz *et al.*, 2006). This difficulty points to a possible extension in SPARROW to allow more than one land area to be associated with a reach.

Another limitation is the difficulty of determining some parameters from calibration to measurements at the catchment outlet. This can be overcome to some degree by imposing model terms or coefficients, but that approach overestimates model confidence. A possible new approach is to use Bayesian methods whereby initial parameter estimates may be specified and then refined by calibration. Another limitation of the current study is the lack of independent validation data. Bootstrapping addresses this to some degree by providing data uncertainty estimates based on data sub-sampling, but ideally a separate data set would be available. SPARROW does not have a temporal component. This could be of concern for erosion modelling, where the observed data may reflect some transitory adjustment to land-use change or catastrophic erosion events.

The SPARROW sediment model is now being incorporated into the CLUES modelling system (Woods *et al.*, 2006b). The sediment model is also being used to refine the source terms in a SPARROW model for phosphorus (as in Elliott *et al.*, 2005).

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