Observed Stream-Bank Movement in Relation to Simulated In-Stream Suspended Sediment Transport

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Abstract. We seek an improved and quantitative understanding of the sources and transport of sediment and attached phosphorus in upland catchments and downstream reaches of the Namoi River in New South Wales, Australia. Study of the sources of phosphorus and related sediment was motivated by severe problems with blooms of blue-green algae and toxic by-products in the Darling and Namoi Rivers. Using atmospheric fallout of radionuclides as tracers, Olley *et al.* (1996) concluded that much of the sediment and associated phosphorus deposited in the lower reaches came from subsoil rather than topsoil. With this insight, we have focussed on quantifying sediment sources from stream-bank and gully erosion, especially in net erosional reaches of Cox's Creek and the Mooki River.

The approach presented here integrates inter-decadal air photography, inter-seasonal field measurements of bank erosion processes, in-stream monitoring of continuous streamflow and turbidity, and event sampling of suspended solids and phosphorus, with hydrologic models of runoff from upland catchments and in-stream suspended sediment transport. We relate a lateral source term in the calibrated transport model to field-based and aerial measurements of stream-bank erosion. This approach gives improved, quantitative understanding of the processes of streamflow and bank erosion due to undercutting, desiccation, block failure, and mass wasting of aggregated particles. These processes interact to produce in-stream fluxes of suspended sediment that are transported and redeposited downstream. Calibration of the in-stream model is illustrated for two reaches of the Mooki River, with the changes in parameter values being related to aspects of the hydraulic geometry and particle size. The combined approach demonstrated here has potential for predictive spatial modelling of sediment concentrations and loads, particularly if the monitoring network can be expanded in space and time.

1. INTRODUCTION

Jakeman *et al.* (1997) give an overview of the modelling framework for looking at sources of phosphorus (P) and sediment in the Namoi River, New South Wales, Australia. The Namoi River Basin is a large (42,000 sq km) tributary to the Darling River in northern NSW, west of the Great Dividing Ranges. Tracer work using ^{137}Cs and ^{210}Pb (Olley *et al.*, 1996) has indicated that much of the sediment in the stream channels is derived from subsoils rather than topsoils. Because P sorbs very strongly to the clayey surface soils, any P from fertiliser application is assumed to remain in the topsoils. This result has broad implications for land use and management, especially in basalt-derived soils that are relatively high in natural P concentration.

Our present goal is to develop and demonstrate appropriate methods for quantifying the flux of P and sediment in the streams from various sources. Beavis *et al.* (1997a) describe the processes and patterns of (sub)soil erosion in two upland sub-catchments of the Namoi. Subsoils are eroded from rills, gullies and stream banks. These features were mapped and analysed at the time scale of decades. Future aerial photography may be obtained at smaller time intervals. Analyses of air photos, however, will remain primarily descriptive and indicative of sediment movement and quantities over a period of decades. Direct estimates of sediment/P loads and in-stream deposition and erosion must come from in-stream and near-stream monitoring and associated models of the processes involved.

2. STREAMFLOW AND SEDIMENT LOAD

Streamflow processes affect the overall sediment yield of a catchment. The systems studied here have catchment areas greater than 100 sq km. At this scale, in-stream sediment transport capacity is the primary control on catchment-average sediment yield (Lane *et al.*, 1997; Renard and Laursen, 1975). That is, the in-stream sediment concentration and load are related strongly to flow. Streamflow also affects the processes of bank erosion (e.g., undercutting, desiccation, block failure, and mass wasting of aggregated particles) that provide local sources of material to the stream.

2.1 Material flux at a single gauging station

Streamflow and material concentration (e.g., suspended sediment and P) are typically measured at a point (and at some temporal frequency) to determine mass balances for a catchment. Empirical relationships between concentration and flow rate at a station may be developed by simple regression or more elegant methods that account for time lags (e.g., Littlewood, 1995). Such methods are useful because flow rate is typically monitored (based on stage) at higher frequency than concentration. Therefore, the flux of material, or 'load', may be computed at a station. Preston *et al.* (1989) discussed the estimation errors associated with different methods of computing load from such data. Subsequently, Green and Short (1995) showed the sensitivity of estimates of P loads to linear relationships between concentration and flow rate in the Namoi Basin.

Gross estimates of sources in a reach between two stations can be computed by subtraction over a given time period. Such estimates include in-stream and near-stream sources, as well as lateral inputs from ungauged tributaries. As with any residual quantity, the uncertainty of the computed difference may be large relative to the estimated value. This is particularly true for noisy and missing data typical of natural systems. Furthermore, simple differencing does not address the temporal dynamics of transport between stations (e.g., particle velocity versus water wave celerity), nor does it allow for discrimination between in-stream and lateral sources.

2.2 In-stream sediment transport

Dietrich and Jakeman (1997) describe a closed-form equation for modelling in-stream sediment transport. We will refer to this model as STARS (Sediment/chemical Transport with Advection, Resuspension and Settling). It is a one-dimensional model of advective transport between two gauging stations (nodes) given flow at both nodes and concentration upstream. Concentration downstream over some period is also required for calibration of the five model parameters. The simulated processes include particle settling, exchange of sediment (deposition and resuspension) between the channel bottom and the water column, plus lateral sources of sediment from bank erosion and sediment inputs associated with local rainfall. These lateral sources are lumped into one constant source term, ρ. See Dietrich and Jakeman for derivations and definitions of model parameters and groupings (e.g., the lateral source term $\gamma = wL\rho$, where w and L are channel dimensions of average width and length). Further details of the model are given in section 3.5 below.

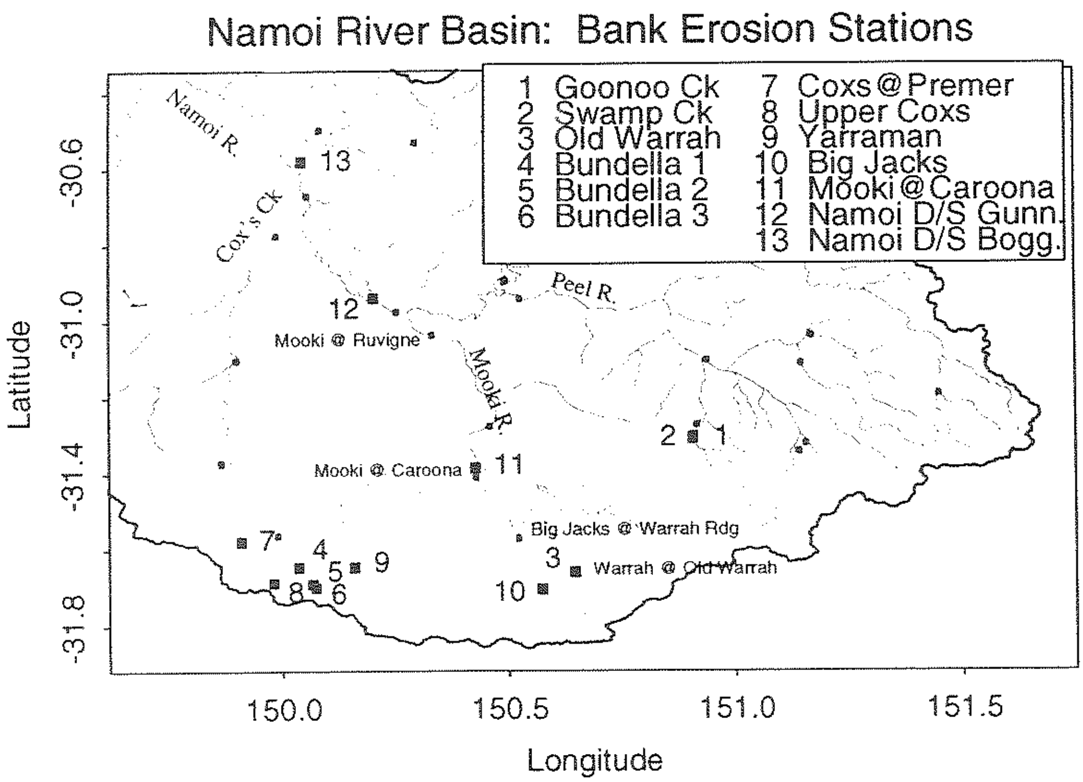

Figure 1. Map of bank erosion monitoring sites (squares) and stream gauges (circles) in the upper Namoi Basin, including the Liverpool Plains. Bank erosion sites 3, 10 and 11 are highlighted in this paper.

2.3 Aerial photography

The use of aerial photographs can provide essential information on longer term rates of bank movement than the field measurements, analyses of in-stream monitoring and modelling presented here. Application of aerial photography, either to document changes in channel form or to estimate rates of erosion/lateral migration, is well documented in the literature (Wolman, 1959; Brizga and Finlayson, 1990; Brooks and Brierley, 1997). The GIS development associated with the present mapping procedure is described in Beavis *et al.* (1997a). Comparison of the maps produced by this method identified channel reaches which had migrated laterally and/or down valley over a period of 50 years. At the coarsest level the total length of stream can be classed into two broad, descriptive categories: channel bends where active erosion occurs, and straight segments where erosion is relatively less significant. Straight segments also may widen in response to increased sediment and flow (Schumm, 1969). This occurred within the upland catchments of the Liverpool Plains for the flood event of January 1996. Therefore, estimation of relative bank stability, incorporating a number of assumptions, can only provide indicative values.

3. METHODS

3.1 Field monitoring of bank erosion

A field campaign to set up and monitor sites for bank erosion was initiated in September 1995. Erosional sites were selected by field reconnaissance where steep bank faces appeared to be active. Most sites are located near stream gauging stations. Figure 1 is a map of established monitoring sites and selected stream gauging stations. This can be compared with the map of sub-catchments (Jakeman *et al.*, 1997, Fig. 2) showing the locations of stream and rain gauges. Most of the bank monitoring sites are in the upper reaches of tributaries to the Mooki River and Cox's Creek, which flow into the Namoi River near Gunnedah and Boggabri, respectively. Previous analyses of flow data and potential sediment loads (Green and Short, 1995) indicated that these ephemeral streams contribute significant portions of the load to the Namoi during high flow months.

Bank movement was monitored at two scales in the field. Bulk lateral movement of the predominantly near-vertical banks was measured by installing survey pegs at known distances from the bank face at several locations along a bend or relatively straight portion, and by measuring distances from a real or "virtual" fence line at a measured bearing. Use of essentially immovable benchmarks proved to be the only sure way to maintain a datum or reference line for the surveying (wooden pegs were often used by cattle as scratching posts, so could be broken or completely dislodged). The accuracy of this type of measurement varied between sites depending upon the use of 'pins' (6 inch nails) near bank faces and upon distances to points of reference. Generally, these lateral measurements were accurate to about 10 cm at each point, and approximately 20 cm averaged over the length of the monitoring site (up to 100 m).

The second approach was to insert marked pins into the face of an active bank (to depths of approx. 10 cm) in a mesh where vertical spacings coincided with soil/sediment units (often at breaks of slope) and horizontal spacing was on the order of 1 m. This method was intended to measure small-scale desiccation and crumbling of the predominantly clayey bank material, some of which is high in smectite mineral content and undergoes significant shrinking as it dries.

3.2 Remote sensing of channel migration

Aerial photographs have been analysed for the Warrah Creek catchment, upstream of Old Warrah, to estimate rates of erosion over a 19 year period, between 1973 and 1992 for the channel bend at Old Warrah. Mapping of Warrah Creek involved tracing the outline of the channel onto a series of overlays to form a mosaic with maximum overlap. This procedure ensures that significant features are located close to the geometric centre of a photograph, and thus minimises distortion effects.

Aerial photographic images of the channel segment at Old Warrah were enlarged to a scale of 1:5,000 using a copy print → negative → print sequence to optimise image resolution and clarity. The tops of stream banks were traced onto overlays and digitised as a series of layers with control points.

3.3 In-stream monitoring

Continuous monitoring stations for flow and turbidity have been installed at twelve locations in the Namoi Basin. Here, we focus on four sites located on the Mooki River and its tributaries (Fig. 1): Mooki River at Ruvigne (419084), Mooki River at Caroona (419034), Big Jack's Creek (419087) and Warrah Creek (419076). Figure 2 also shows the positions of these stations in a vertical profile of the Mooki River system starting from Ruvigne and going upstream. The elevations in this figure have been limited to 600 m to highlight the reaches simulated below. The headwaters of the Mooki River, however, extend up to approximately 1200 m AHD. 'Continuous' (6-minute) data have been averaged over daily time intervals for analysis. In addition to this continuous data, event and routine biweekly samples are taken for flow and water quality parameters including turbidity, suspended sediment (SS) and total P concentrations (Bruce Cooper, pers. comm.).

These less frequent samples are used to correlate material concentration with turbidity or flow rate. The sediment-turbidity relationship is then used to convert time series of measured turbidity to estimated SS concentration. If turbidity is missing for a period but flow rate has been measured, the SS-flow relationship is used to fill in missing data. The correlations are generally non-linear with flow rate, and can be described using power functions (log-log linear). In several cases, there is an apparent data quality problem with the in-stream continuous turbidity probes. This limited the length of continuous records available for analyses at two stations. All of the data presented here have been screened and adjusted where necessary.

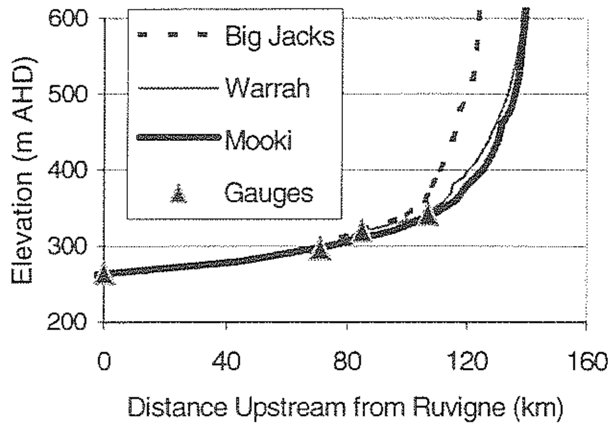

Figure 2. Vertical profile of the Mooki River System, including Big Jack's and Warrah Creek. Stream gauging stations (triangles) from left to right are Mooki @ Ruvigne, Mooki @ Caroona, Big Jacks @ Warrah Ridge and Warrah @ Old Warrah (cf. Figure 1).

3.4 Catchment rainfall-runoff model

When streamflow data is missing or questionable, it becomes important to fill in missing data or even estimate flow at ungauged sites. Beavis *et al.* (1997b) discuss the use of a rainfall-runoff model (IHACRES) for the Peel River upstream of Chaffey Dam. This model will also be used to estimate stream flow from other upland catchments based on calibration to observed runoff. Jakeman *et al.* (this issue) discussed the overall modelling framework, including the use of IHACRES for streamflow simulation. The simulation of in-stream transport demonstrated here for the Mooki River relies on measured streamflow, turbidity and suspended sediment. However, application to the greater Namoi stream network will require use of catchment runoff simulation to estimate flows at the upstream stations of erosional reaches.

3.5 In-stream transport model

The STARS model is applied to two reaches of the Mooki River for illustration. All of the Mooki and its tributaries are ephemeral, and the lower reaches can have significant losses during low-flow periods or gains from lateral inflows during high-flow periods, such that the conditions for matching observed data are not ideal. The model compensates for differences in flow between upstream and downstream nodes by computing an average flow rate over the reach, Q_t.

The scaled equation for downstream suspended sediment concentration c_L as a function of time t is:

$$c_L(t) = c_0(t-\tau)e^{-\alpha/Q_t} + \left\{\frac{\beta\eta(Q_t - Q_*)^{\mu} + \gamma}{\alpha}\right\}\left\{1 - e^{-\alpha/Q_t}\right\} \qquad (1)$$

where c_0 is the concentration upstream, τ is the effective water parcel travel time estimated from the data, and $\eta = 1$ for $Q_t > Q_*$, otherwise $\eta = 0$. Essentially three processes are simulated: in-channel deposition, lateral sources, and re-suspension. Deposition is controlled by the particle settling velocity via α, lateral sources are given by γ, and resuspension is determined by a combination of β, Q_* and μ. These five model parameters (cf. Dietrich and Jakeman, 1997) are calibrated for each reach and time period using a combination of quadratic programming and brute force. Quadratic programming (IMSL, 1991) is used to estimate values of two parameters (β, related to bed sediment concentration, and γ, the lateral source strength) for fixed values of the other three. The parameter β is constrained to be non-negative, such that the resulting simulated re-suspension cannot be negative. The parameter space for the three "fixed" values (α, Q^* and μ) is gridded, and the constrained optimisation problem is solved for each grid point, for which the root mean squared error (RMSE) and bias between observed and simulated time series are computed. When the optimal parameter set was not consistent for both measures of fit, the RMSE was used as the sole criterion.

For the case where multiple tributaries were gauged in parallel for the upstream "node", e.g., for the upper Mooki River, flow rates were summed and weighted by the ratio of downstream to upstream flow volumes over the period of simulation:

$$q_0 = \frac{\sum q_L}{\sum\left(q_{0_1} + q_{0_2}\right)}\left(q_{0_1} + q_{0_2}\right) \qquad (2)$$

where q is flow rate, $\sum q$ is cumulative flow over the calibration period, and the subscripts designate the gauging stations at two upstream (q_{0_1} and q_{0_2}) and one downstream (q_L) locations, as well as the combined upstream value (q_0). Equation 2 ensures mass conservation over the period of summation.

The concentrations for the upstream "node" are the flow-weighted averages of the values at stations 1 and 2 for each day:

$$c_0 = \frac{c_{01}q_{01} + c_{02}q_{02}}{q_{01} + q_{02}} \qquad (3)$$

All of the flows and concentrations are functions of time (daily values here).

Two reaches of the Mooki River and its upland tributaries are calibrated for illustration here. The upper "reach" is actually a combination of Warrah Creek gauged at Old Warrah and Big Jack's Creek at Warrah Ridge with the Mooki River down to Caroona. The average distance from upstream stations to the downstream station is approximately 60 km. The lower reach is approximately 87 km from Caroona to Ruvigne above the confluence with the Namoi River (Figure 1).

4. RESULTS

4.1 Observed processes of bank erosion

Streamflow plays an important role in every bank erosion process by transporting material away from the base, directly undercutting or otherwise scouring the banks, or by affecting the water content and associated mechanical properties. However, the rate of lateral migration of the banks did not necessarily coincide with the periods of highest flow. For example, we found debris over-bank at one site on Goonoo Goonoo Creek (#2 in Fig. 1) following a summer flood event, but the rate of bank movement was not accelerated. Typically, banks are steepened during the winter due to material removal from the base at intermediate flow rates. At the Old Warrah site (#3), we also observed soil piping (approx. 10 cm diameter) at semi-regular intervals above a heavy clay layer. There were no signs of local surface inflows at Old Warrah, whereas the site on Cox's Creek at Premer (#7) had several rills that became active during the study period.

The two dominant forms of observed bank erosion were tensile block failure along vertical cracks and mass wasting of clayey aggregates (typically 10 to 40 mm diameter) following drying and desiccation of the banks. Classic rotational slumping along a distinct failure surface was not observed, but less pronounced slumping involving both horizontal and some vertical movement was observed. Although changes in the bulk density were apparent under such conditions, the expansion was not quantified. In the estimates of bank erosion rates below, changes in volume are equated with a proportional change in the mass of sediment stored in (and thus released from) the banks.

4.2 Measured rates of bank erosion

The volume of material entering the stream from bank erosion over a period can be computed from the change between consecutive monitoring dates:

$$V = \int_0^l \{y(x,t_1) - y(x,t_2)\} \cdot z(x)\,dx \qquad (4)$$

where x is the distance along a line of reference (typically a fence line), y is the distance to the bank perpendicular to this line, $z(x)$ is the bank height (approximately uniform for each site), l is the length of the line of reference (not equal to the curvilinear bank length), and t_i is the time of monitoring. Rates of mass movement can be estimated by multiplying V by an average dry bulk density and dividing by the time period (t_2-t_1).

An example of observed bank movement is shown in plan view for Warrah Creek in Figure 3. The computed volume of material from this bend equals 270 m^3 from 20 July 1996 to 22 July 1997. The estimated source strength, ρ, over this length and time is 14 kg d^{-1} m^{-1} (using z = 4.0 m and an average dry bulk density of 1.4 g/cm^3).

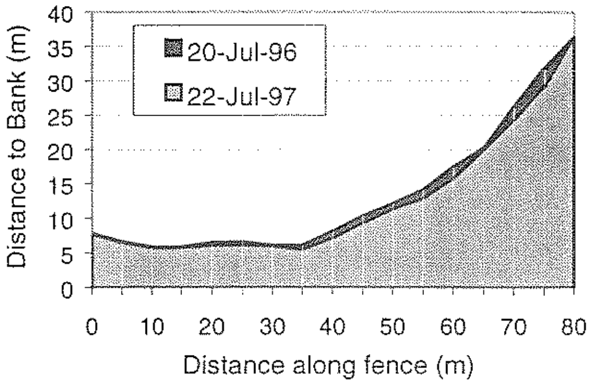

Figure 3. Plan view of the meander on Warrah Creek at Old Warrah (Site #3) approximately 200 m upstream of stream gauging station.

4.3 Estimates from aerial photography

Over a nineteen year period, significant lateral movement of the stream bank was evident at Old Warrah (site #3). Transects were taken at 10m intervals along a 130m length of stream bank to estimate a mean value of annual stream-bank recession rates equal to 0.33 m a^{-1}. Differences in ground-surface area between the images were measured and, for an average stream-bank depth of 4.0 m, based on field data, it was estimated that 0.60 m^3 a^{-1} was eroded per metre length of exposed stream bank (ρ = 5.1 kg d^{-1} m^{-1}). This estimate is based on the assumption that bank profiles are of a consistent form as the bank recedes laterally. Over the field sampling period, some banks collapsed and/or crumbled, while others steepened or remained near vertical.

Comparison of historic and current aerial photographs has provided the basis for identifying relative stability in channel segments and establishing proportional lengths of active and stable stream banks. Using this classification, 64% of Warrah Creek comprises actively eroding sites, with the remaining 34% representing short, straight segments. Thus, the bank source strength for Warrah Creek is estimated to be 3.2 kg d^{-1} m^{-1} over 19 years or 8.9 kg d^{-1} m^{-1} for 1996/97. Comparison of historical photographs indicates that the orientation of short, straight segments in the upper catchment remains relatively static and may be controlled by geological factors. However, where the creek incises deep alluvium, a number of straight segments mapped from the 1992 photographs are sites of channel avulsion.

4.4 Model calibration and estimation of the transport parameters

Results of the STARS model calibration for two reaches of the Mooki River (discussed above) are shown in Figure 4. STARS was calibrated to daily estimates of suspended sediment (SS) concentration shown in the upper panels to minimise the RMSE. The sediment loads in the lower panels are computed by multiplying observed and simulated concentrations by recorded daily flow rates. This shows the importance of estimating concentrations most accurately during high-flow events if sediment yield or load is of primary concern. Fluctuations in SS during lower flow were more difficult to simulate. This could be due to the level of noise in the data associated with silting of the turbidity probes during low flow, and the potential for in-channel disturbances (e.g., road traffic, construction or animal movement) to raise concentrations arbitrarily at relatively low flow.

In Figure 4a, the best fit to SS concentration (not to load directly) involved a significant lateral source that resulted in a fairly constant concentration at low flow. Initially, the same type of fit was obtained for the Upper Mooki also, but the fit to concentration during a portion of the low-flow periods was improved by manual calibration, while keeping a relatively good fit for high flows. The load is simulated well in both cases.

Table 1 shows the calibrated model parameter values for both reaches of the Mooki River. The absolute and relative values of the parameters are consistent with a physical/conceptual interpretation of their effects, despite the various assumptions required to obtain an analytical solution.

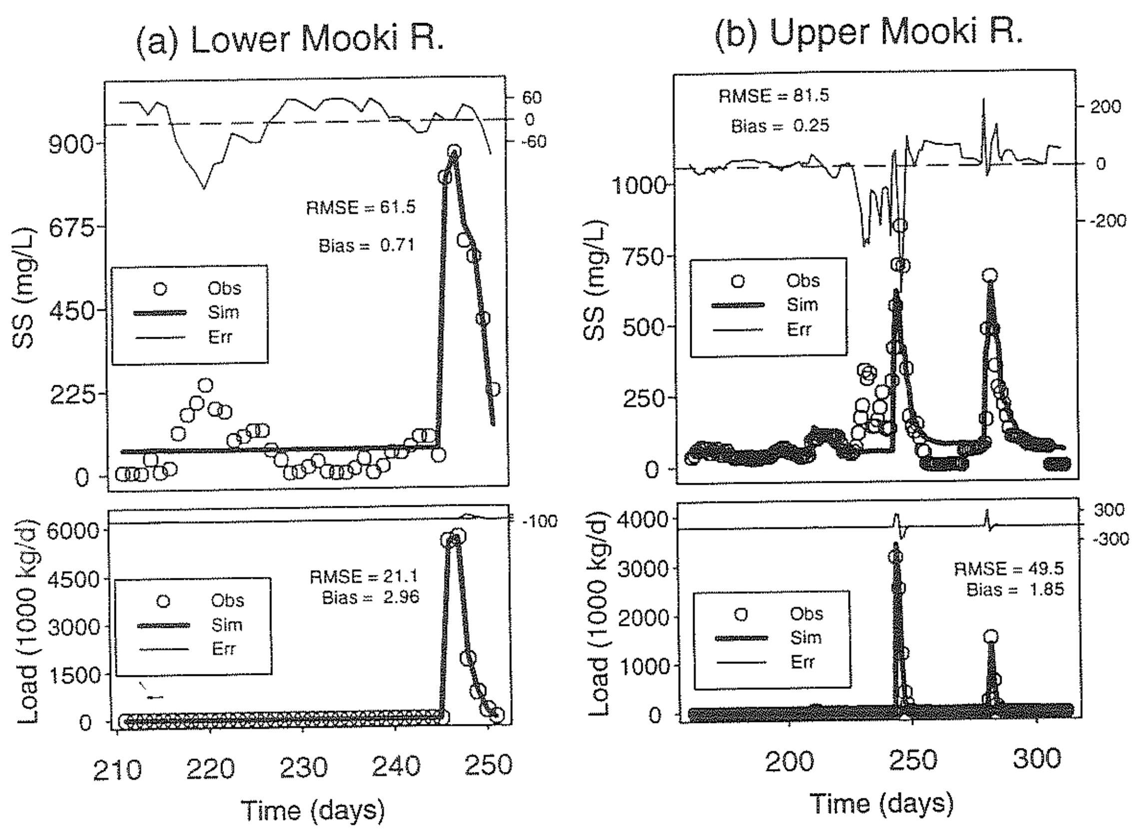

Figure 4. STARS calibration to downstream suspended sediment concentration showing the direct model fit to concentration data (top) and the resulting estimates of sediment load (bottom) for (a) Lower Mooki River from Caroona to Ruvigne and (b) Upper Mooki by combining Warrah and Big Jacks Creeks upstream with flow adjustment to the Mooki River at Caroona. Times for both simulations are the day of the year, 1996, with the largest recorded event occurring around 7 September 1996.

Qualitatively, the relative values of α for these two reaches reflect a higher settling velocity and median particle size in the upper reach, as one might expect. These values of α are orders of magnitude greater than those found for the Murrumbidgee and Murray Rivers (Dietrich and Jakeman, 1997). This relates to the average particle sizes and lengths of the river reaches. A semi-quantitative test of the values obtained here is possible by computing the Stokes particle settling velocity for a given particle size (Allen, 1985, p. 46).

This estimate for a single particle in quiescent water will tend to over-estimate the settling velocity compared with turbulent conditions and high particle concentrations. The particle diameters based on the Stokes velocities are 2.5 μm (fine silt) and 14 μm (medium silt) for the lower and upper reaches, respectively. This is consistent with observed median particle sizes.

Table 1. Calibrated STARS model parameters for reaches of the Lower and Upper Mooki River.

Parameter	Lower	Upper
α	445	5 250
γ	29 435	194 500
β	97 400	54 000
$Q_{\bullet}$	3 600	1.5
μ	0.365	0.465

Other model parameters may also be indicative of the relative behaviours and dominant processes in these reaches. High values of both β and γ indicate that, indeed, the sediment loads are limited by in-stream transport capacity rather than being sediment limited. The relative values between the Lower and Upper reaches also indicate that lateral sources (presumably dominated by bank erosion) are more active in the upper reach, while the bed concentration of entrainable sediment (i.e., that which is readily re-suspended) is greater in the lower reach. Both of these results are consistent with our descriptive field observations. Furthermore, $Q_{\bullet}$ is related to the critical bottom shear stress for incipient motion (Shen and Julian, 1993) which is proportional to the hydraulic gradient and inversely proportional to the median (or the 30th percentile) grain size. From Figure 2, we see that the stream gradient (an approximation for the average hydraulic gradient) is similar, though greater in the upper reach, while the grain size may differ by an order of magnitude based on the values above. This supports only the direction of the difference in $Q_{\bullet}$ and not necessarily the magnitude.

Finally, we assess the calibrated lateral source term. The scaled source term in STARS, $\gamma = \overline{\rho} L$, has units of kg d^{-1}, where $\overline{\rho}$ is the effective net source strength of the reach in kg d^{-1} km^{-1} (10^{-3} kg d^{-1} m^{-1}). Assuming that all "active" sub-reaches (from air photo analyses above) erode at a rate equal to that measured at the monitoring site, and ignoring over-bank deposition within the reach (i.e., assuming that all deposition occurs in the channel) yields $\overline{\rho} = 1000 \cdot \phi \rho$, where ϕ is the fraction of actively eroding channel, estimated to be 0.64 for Warrah Creek. This value represents total, rather than net, bank erosion by ignoring parallel depositional sites on the insides of bends. Thus, it should serve as an upper bound on net erosion. The estimated values of $\overline{\rho}$ for Warrah Creek range from 3200 kg d^{-1} km^{-1} based on air photos to 8900 kg d^{-1} km^{-1} based on field measurements, noting that the latter reflects only one year, versus 19 years. If the latter value is applied to the entire upper reach, the field estimated value would be approximately 220,000 kg d^{-1} which agrees remarkably well with the simulated value in Table 1. There is, of course, large uncertainty assigned to estimates derived from both the model and field/remotely-sensed data. Each was estimated independently, however, without attempting to match values. It remains to be shown that such results are reproducible for other streams.

5. DISCUSSION

Natural processes such as sediment and nutrient transport over large scales involve multifaceted interactions between climatic variability, catchment runoff, streamflow dynamics, fluvial morphology and small-scale soil mechanics. Several methods for measurement and data interpretation were combined and demonstrated for the assessment of material sources and transport between gauging stations. Parameter values of the calibrated SS transport model (STARS) were consistent with a physical interpretation of the sources and sinks within two monitored reaches of the Mooki River. The quantitative agreement between simulated "lateral sources" and measured bank erosion was surprisingly good. This degree of agreement is not expected in general due to both data and model uncertainty, as well as the crude method of scaling up essentially point measurements to large stream reaches.

Several refinements to the approach can be explored in addition to further testing on other parts of the stream network. Although the lumped, flow-weighted concentration upstream did not appear to unduly bias the results, it is possible to explicitly compute transport for each tributary from upstream gauging stations to an ungauged node at the confluence as an intermediate step. Parameter values for each reach may be constrained by knowledge of the physical system (e.g., hydraulic geometry and channel/bank material). Further insight to the system behaviour may also be gained by separate calibration for periods of high and low flows.

The combined approach demonstrated here has potential for predictive modelling of sediment concentrations and loads, particularly if the monitoring network can be expanded in space and time. The ongoing aim is to further quantify and characterise the sources and movement of sediment and P by applying STARS (or its offspring) to more streams in the Namoi Basin using the latest in-stream and bank erosion data. Subsequently, model results over the recorded period may be hind-casted using historical streamflow and related to channel migration observed over several decades by aerial photography.

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