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CSIRO Land and Water, Canberra
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Introduction

This document describes methods used in the NLWRA rivers and sustainable agriculture projects to represent the erosion of sediment from riverbanks and the propagation of gully, hillslope and riverbank sourced sediment through a river network. Essentially it describes methods for constructing sediment budgets through river networks. The budgets include storage of sediment on floodplains, in the bed of the river and in reservoirs. Calculations are made of the sediment output from each river link and the contribution of sediment to the coast, or any other receiving body, from all sub-catchments. The budgets treat two types of sediment: suspended sediment and bedload. A suit of ArcInfo™ programs are used to define river networks and their sub-catchments; import required data; implement the model; and compile the results. These are referred to collectively as the SedNet model: the Sediment River Network Model.

For this project, suspended sediment is characterised as fine textured sediment carried at relatively uniform concentration through the water column during large flows. Its transport is generally limited by the supply of sediment to rivers rather than by the sediment transport capacity (Olive and Walker, 1982; Williams, 1989). The main process for net deposition of suspended sediment is overbank deposition on floodplains (e.g. Walling et al., 1992). The amount of deposition depends upon the residence time of water on the floodplain and the sediment concentration of flood flows. The velocities of suspended material within channels are relatively high so we can assume that its residence time is low, that there is negligible transient deposition of suspended sediment, and that steady state conditions have been reached since European settlement increased the supply of sediment. Suspended sediment is sourced from surface wash erosion of hillslopes, gully erosion and riverbank erosion. The sediment budget is reported as mean annual values for either the current land use or for pre-European native vegetation cover.

Bedload is sediment transported in greatest proportions near the bed of a river. It may be transported by rolling, saltation, or for short periods of time, by suspension. Transport occurs during periods of high flow, over distances of hundreds to thousands of metres (Nicholas et al., 1995). Residence times of coarse sediment in river networks are relatively long so there is transient deposition on the bed as the sediment works its way through the river network. In addition to that deposition, an increase in sediment supply from accelerated post-European erosion can cause the total supply of sediment in historical times to exceed the capacity of a river reach to transport sediment downstream. The excess sediment will be stored on the bed and the river will have aggraded over historical times (Trimble, 1981; Meade 1982). There has been a significant increase in supply of sand and fine gravel to rivers in historical times and deposition of this bedload has formed sand slugs: extensive, flat sheets of sand deposited over previously diverse benthic habitat (Nicholas et al., 1995; Rutherfurd, 1996). The bedload budget aims to predict the formation of these sand slugs.

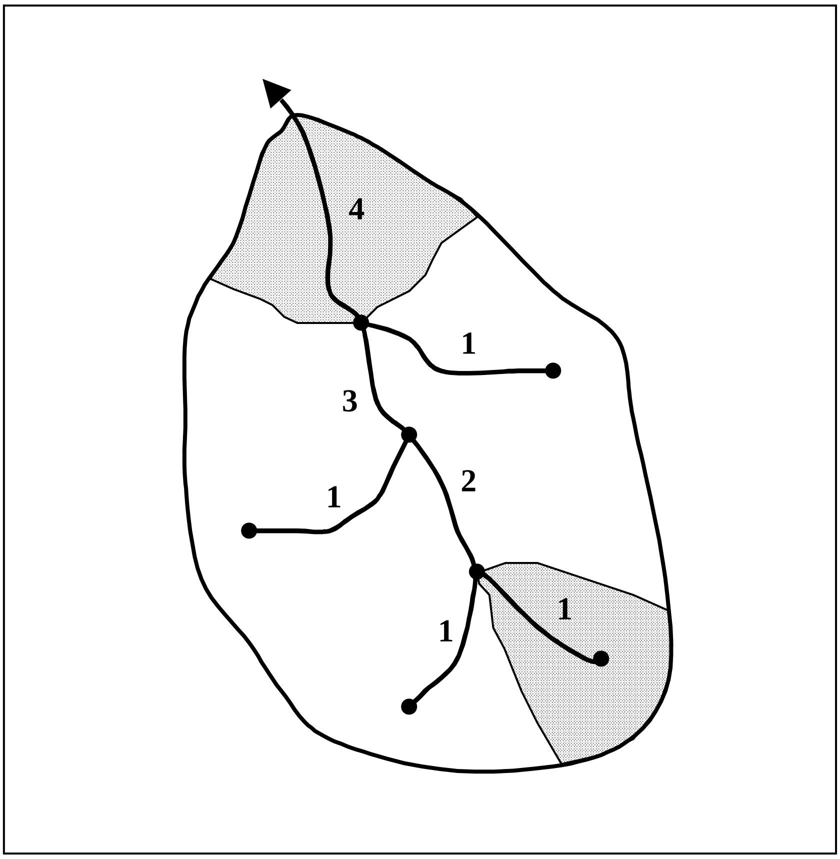

Figure 1. A river network showing links, nodes, Shreve magnitude of each link and internal catchment area of a magnitude one and a magnitude four link.

The basic unit of calculation for constructing the sediment budgets is a link in a river network. A link is the stretch of river between any two stream junctions (or nodes; Figure 1). Each link has an internal sub-catchment, from which sediment is delivered to the river network by hillslope and gully erosion processes. The internal catchment area is the catchment area.

added to the link between its upper and lower limits (Figure 1). For the purpose of the model, the internal catchment area of first order streams is the entire catchment area of the river link. Additional sediment is supplied from bank erosion along the link and from any tributaries to the link

Definition of River Links

A branching network of river links joined by nodes was defined from the AUSLIG 9" digital elevation model (DEM) of Australia. The alternative method of defining river networks from mapped streams was dismissed because in places the position of the mapped streams does not coincide exactly with valleys in the DEM. The DEM is required to generate topographic attributes of catchment area and slope of each river link and errors in positioning produce many spurious results.

The Arc Info flow accumulation algorithm was used to define the catchment area of all cells in the DEM. The river network was defined as beginning at a catchment area of 50 km^2. This was an arbitrary choice used to limit the number of links across the assessment area, while still representing all large streams. The physical stream network extends well upstream of the limit in most areas and these areas are treated as part of the internal catchment area contributing material to the river link. Short links, where the catchment area had reached less than 75 km^2 by the downstream node were removed.

Links were further separated by nodes at the entry to and exit from reservoirs and lakes. The presence of lakes and reservoirs was derived from an AUSLIG waterbody database mapped from 1:2.5M topographic maps. This database was found to unreliably distinguish natural lakes from waterbodies created or regulated by dams. A separate AWRAC point coverage of flow control structures was obtained to defined regulated waterbodies from natural lakes. We defined lakes as those waterbodies which did not intersect an associated structure in the dam database. We defined reservoirs as waterbodies which intersected structures of 10 m height or greater. The storage capacity of the reservoir was recorded in the river link database and all river links downstream of reservoirs were defined as having regulated flow.

Internal catchment areas for each link were determined from the flow accumulation grid. The slope of the link was defined as the elevation difference between the upper and lower ends of the link divided by the length of the link arc. An eight digit unique identifier was given to each link, composed of the four digit AWRC basin identifier followed by an arbitrarily assigned four digit code. A Shreve magnitude (Shreve, 1966), a form of stream ordering, was assigned to each reach for the purpose of determining the sequence of link processing when implementing SedNet through a river basin.

As a check, links were compared with named streamlines recorded on the AUSLIG 250K topographic map series. A close match was found in all upland areas (areas with ridge and valley topography). If links did not coincide with a named stream they were excluded from our database. This process was necessary in the drier and flatter regions to remove DEM generated flow accumulations that are not expressed on the ground as streams for reasons such as transmission losses, dispersion of flow, terminal lakes, or lack of flow through dune systems and depressions (Figure 2). The MDB stream network was also manually checked and edited against the 72 1:250,000 topographic map sheets that cover the basin. The lowlands of the MDB are not well represented by the link network because of problems of anabranching streams, distributary channels, and flow through very flat areas not well represented by the DEM. Accurate representation of this area requires further development, and the results in lowland MDB should be treated as being unreliable. The final network across the assessment area of river basins containing intensive land use is composed of approximately 14,000 links.

Sediment Budget for Bedload

A sediment mass budget for bedload was calculated for each river link (x) in a network. The mass balance is evaluated at the outlet of each link, with the aim of defining those links subject to net deposition because the historical supply of bedload has exceeded sediment transport capacity. The total load supplied to the outlet of the link at any time is compared with the sediment transport capacity at that point. If the load is in excess of capacity, the excess is deposited and the yield to the link immediately downstream equals the sediment transport capacity. If the loading to the outlet is less than the sediment transport capacity there is no net deposition and the yield downstream equals the loading to the outlet.

Two forms of the coarse sediment model were implemented. The first model dealt explicitly with transient storage resulting from the long residence time of bedload within rivers in relation to the time since European settlement when erosion increased. The second model is a simpler steady state bedload sediment budget for post-European conditions. Comparison of the two models provides valuable insights into the factors controlling bed deposition in Australian rivers.

Transient Model

The simplest conceptualisation of current transport of coarse sediment in our river systems is to view human impact on erosion as a step function, where the input of sediment from any point in a catchment increased soon after clearing of the catchment and has continued at a steady, high rate since (Figure 2). Figure 2 is a gross simplification of the erosion history of catchments. In many cases there was probably a pulse of very high erosion at some time after clearing, representing gully and river expansion, with subsequent decline in erosion over the following decades. That pulse could be simulated by the transient model if we knew its shape and time of initiation but to our knowledge such information is available quantitatively for only one tributary stream (Wasson et al., 1998). The shape of the pulse and its timing not only differs between river basins, but also within river basins. For example, gully erosion began in the Hunter R. catchment in the 1830's but the main pulse of river expansion was in the 1950's (Melville and Erskine, 1986; Erskine and Bell, 1982).

For the transient model we assumed that the step occurred 100 y ago. As will be shown below the lack of precision in the timing of erosion has little influence on the results. We assumed that the input of bedload prior to European settlement was negligible compared to current loads in impacted rivers, and that relative to the post-European conditions there was a negligible rate of net aggradation of sediment. The magnitude of the stepped increase in supply varies between river links depending upon the time averaged intensity of gully and riverbank erosion.

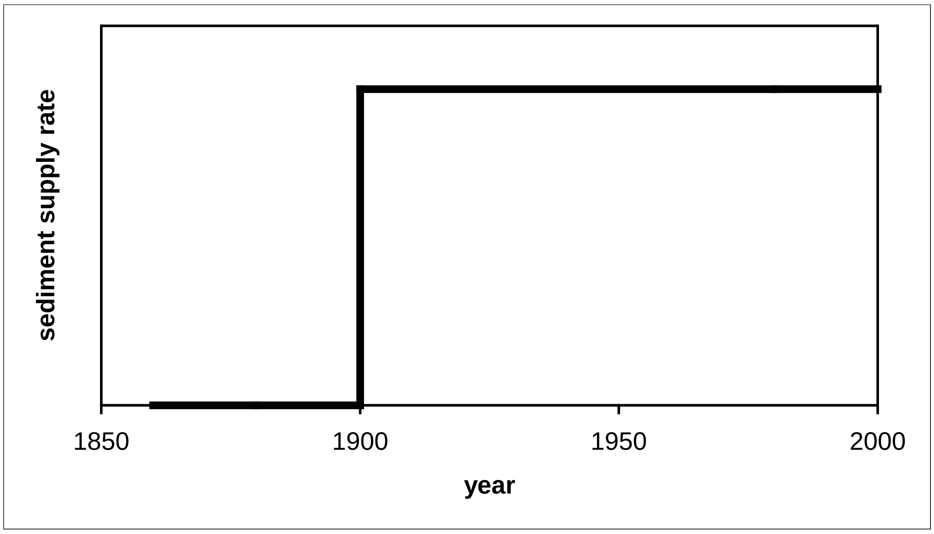

Figure 2. Modelled stepped increase in input of coarse sediment to a river link 100 y ago.

The step function of sediment supply to a river link moves gradually downstream at a rate determined by the average velocity of sediment transport in the link; that is the velocity of the sediment including periods of rest between transport events. The inverse of the sediment velocity is its residence time: the average time taken for the bedload to pass through a river link. The residence time represents the lag in time for an upstream step in sediment supply to work its way through a river link. Diffusion of the step function can also occur but was not simulated. The transient model incorporates the residence time of sediment in a link by computing the sediment budget at an annual time step over the 100 y of the step function.

Inputs of Bedload

Bedload inputs to a river link come from: tributaries immediately upstream of the link; erosion of the river banks along the link; and lateral inputs from gully erosion in the surrounding internal catchment area (Figure 3). Sheetwash and rill erosion of hillslopes provide negligible bedload to rivers.

The tributary input in year t to the upstream node of a link (TC_{xt}, t/y; where C means coarse textured sediment) is merely the sum of bedload sediment yields from upstream tributaries (YC_{nt}; t/y):

$$TC_{xt} = \sum_{1}^{n} YC_{nt} \tag{1}$$

where n is the number of tributaries feeding the upstream node.

The rate of bank erosion along the river link was calculated from the results of a global review of river bank migration data (Rutherfurd, 2000). The best predictor of bank erosion rate (BE; m/y) was found by Rutherfurd to be bankfull discharge ($Q_{1.58}$; m^3/s; see hydrology section below for discussion):

$$BE = 0.008 Q_{1.58}{}^{0.60}. \tag{2}$$

The coefficient in Equation (2) is half of that derived from the global review. This was found to give the most realistic results averaged over the 100 y to which the rule was applied, and reflects the generally low bank erosion rate found in Australia. The mass of sediment contributed from bank erosion over a river link is the product of the bank erosion rate, the length of the link (L_x, km), the bank height, and the sediment bulk density (ρ, t/m^3). Bank erosion contributes to both suspended and bedload. Limited available data and field observations of bank texture suggest a relatively even contribution to each form of sediment (e.g. Dietrich and Dunne, 1978) thus the proportion contributed to bedload (PB) was set to 0.5. Values of 3 m for bank height and 1.5 t/m^3 for bulk density were used in the model. Consequently the mean annual supply of sediment from bank erosion along a link (BC_x, t/y) can be calculated as:

$$BC_x = 18 (Q_{1..58})^{0.6} L_x \tag{3}$$

Riparian vegetation exerts a strong control on riverbank erosion. Streams with preserved native riparian vegetation erode at either a very slow rate or are resistant to any erosion except under extreme conditions. Clearing of riparian vegetation makes banks more susceptible to mass failure (Abernethy and Rutherfurd, 2000), fluvial scour (Hickin, 1984; Prosser et al.,

2000) or catastrophic erosion during floods (Brooks and Brierley, 1997; Brooks, 1999). We consequently restricted the application of Equation (3) to parts of the river network that were cleared of native riparian vegetation. The final equation used to predict the mean annual supply of sediment from bank erosion along a link was thus:

$$BC_x = 18(1 - PR)(Q_{1..58})^{0.6} L_x \tag{4}$$

where *PR* is the proportion of stream length with intact native riparian vegetation.

The proportion of native riparian vegetation was determined by intersection of the river network with a grid of native vegetation in 1995 obtained from the Australian Land Cover Change project at a resolution of 100 m (BRS, 2000). This is the best available data but is still a crude measure of riparian condition. The 100 m resolution fails to identify narrow bands of remnant riparian vegetation in cleared areas but it also fails to identify narrow valleys of cleared land penetrating otherwise uncleared land.

The amount of sediment delivered from gully erosion in the internal catchment area of a river link was derived from intersection of a grid of gully density with the internal catchment area of a link. Production of the gully erosion grid is described in Hughes et al., (2001). The mean annual delivery of coarse sediment from gully erosion within the internal catchment of link *x* (GC_x , t/y) is

$$GC_x = \frac{1000 a \rho \alpha (PG_j)}{\tau} \sum_{j=1}^{j=n} GD_j \tag{5}$$

where a is the area of the internal catchment (km^2); ρ is the density of sediment (t/m^3); α is the mean cross sectional area of a gully (m^2); τ is the age of the gully (y); PG_j is the proportion of gully material that contributes to bedload; GD_j is the gully density (km/km^2) of each cell j in the internal catchment area; and n is the total number of cells in the internal catchment area. Studies of gully morphology were used to ascertain a mean value of 10 m^2 for alpha; ρ was set to 1.5; *PG* was set to 0.5, as it was for bank erosion; and τ was set to 100 y to be consistent with the time step for increase in sediment supply. Adopting these values

$$GC_x = 150 a \sum_{j=1}^{j=n} GD_j \; . \tag{6}$$

Sediment Transport Capacity

The sediment transport capacity of flow is a function of discharge, hydraulic gradient, hydraulic roughness, particle size and channel width. The function is often expressed in terms of unit stream power, flow velocity or boundary shear stress but has a common form (Julien and Simons 1985):

$$\frac{STC_x}{w_x} = k_1 \left(\frac{Q_x}{w_x} \right)^{\beta} S_x^{\ \gamma} \tag{7}$$

where *STC* is sediment transport capacity, k_1 is a constant which includes hydraulic roughness and particle size; *Q* is discharge and *S* is the energy gradient, approximated as the sine of channel slope. A review of available data shows that the exponents β and γ have a limited range from 0.9 to 1.8 with a median of 1.4 (Prosser and Rustomji, 2000). Because of the huge range in *Q* and *S* within a basin, the range of exponent values has little influence on the basin wide patterns of sediment transport capacity (Rustomji and Prosser, 2001). Equations for sediment transport capacity can include a threshold for incipient motion (see review by Buffington and Montgomery, 1997) but its definition has been criticised (Lavelle and Mofjeld, 1987). A value of $\beta > 1$ has the same practical effect as a threshold for motion, producing ineffective sediment transport at low *Q*.

Models usually incorporate the influence of flow on sediment transport by taking a dynamic approach. They solve water and sediment transport equations over small increments of time and space (e.g. Dietrich et al., 1999). Regional assessment of sediment storage then requires integration of the results (often daily flows) over several decades to examine the net effect of historical sediment loads. Discharge is the only term that varies over time, so an alternative approach is to integrate the flow record over time to calculate integrated STC:

$$\int STC_x dt = k_1 w_x^{\ 1-\beta} S_x^{\ \gamma} \int \left(Q_x - Q_{f\,x} \right)^{\beta} dt \tag{8}$$

where Q_{fx} is the component of flow in link *x* that goes overbank and does not contribute to bedload transport in the channel. As is commonly adopted, the bankfull discharge was set to the magnitude of the 1.58 y recurrence interval flood (Richards, 1982). Conceptually, the integration of discharge in Equation (8) is the same as transforming the flow duration curve (Dunne and Leopold, 1978) to the power of β and integrating to obtain the total sediment transport capacity applied. That is, the effect of variable flow can be treated in a probabilistic manner, to fit an observed distribution, rather than as deterministic prediction of time varying flow. The integrated influence of discharge on sediment transport capacity can be calculated at gauging stations and the result regionalised to ungauged basins (e.g. Pilgrim, 1987).

There are several advantages to this probabilistic approach. Firstly there is no need to calibrate a flood routing model. Second it is computationally more efficient as there is no need to calculate flow in each link for each day. Third it is often not possible to get good prediction of spatial patterns of daily flow because of the sparse network of rainfall stations. Given that there is no need to deterministically predict daily flow to examine net sediment patterns it is better to use a term which represents the net effect of discharge. In the project we implemented the probabilistic approach by summing daily $Q_x^{\ 1.4}$ over one hundred years of record (see *Hydrology* below) and averaging to produce a mean annual value.

Reviewing an extensive data set of river loads, Yang (1973) found strong relationships between unit stream power and *STC*. His relationships produce a value of $\beta = 1.4$ and $\gamma = 1.3$, close to the median values of all studies reviewed (Prosser and Rustomji, 2000). Using Yang's (1973) equation, and average value for Mannings roughness coefficient of 0.025, we predicted sediment transport capacity in a river link (t/y) from:

$$STC_x = \frac{86 S_x^{\ 1.3} \sum Q_x^{\ 1.4}}{\omega w_x^{\ 0.4}} \qquad (9)$$

where $\Sigma Q_x^{1.4}$ represents mean annual sum of the daily flow record ($\mathrm{Ml}^{1.4}$/y); and ω is the settling velocity of the bedload particles (m/s).

River width is often calculated from bank full discharge values using empirical rules of hydraulic geometry (Leopold and Maddock, 1953):

$$w_x = k_5 Q_{1.58}^{\ e}. \qquad (10)$$

Reviews of hydraulic geometry show that $e = 0.5$ in most cases. We made 334 measurements of river width from aerial photographs across the NLWRA regions. Regressions of these measurements against predicted bankfull discharge produced poor results. As described below, bankfull discharge was predicted from rainfall and catchment area (*A*, ha), and making predictions directly from those variables, rather than bankfull discharge, was examined using multiple regression. Other available parameters which might influence river width were added to the list of independent variables. These were proportion of riparian vegetation, channel slope (S), and floodplain width (F, m; see Pickup and Marks, 2001 for details). The best results were produced by dividing the regions up into three groups. For the Burdekin river basin (r^2 = 0.55, n = 118):

$$w_x = 0.092 A_x^{0.34} F_x^{0.5} S_x^{0.29} . \tag{11a}$$

For the MDB (r^2 = 0.64, n = 108):

$$w_x = 0.2 A_x^{0.24} F_x^{0.26} . \tag{11b}$$

For the remaining basins (r^2 = 0.37; n = 108):

$$w_x = 4.07 A_x^{0.16} S_x^{-0.12} . \tag{11c}$$

Construction of the Bedload Budget

The transient budget for bedload was evaluated sequentially from the top of a basin to the outlet by increasing Shreve magnitude (Shreve, 1966) of each river link. The budget was evaluated at each link for each year t from t = 0 to 100 y. The mass balance compared the total loading at the link outlet for each year (TLC_{xt}) with the mean annual sediment transport capacity of the link (STC_x).

Bedload inputs from all sources were set to zero at time t = 0. Bedload inputs to the outlet come from tributary yield of bedload and lateral inputs from gully erosion and riverbank erosion. Inputs from upstream tributaries reach the link outlet at time (t+tr_x), where t is the time of input and tr is the residence time of sediment in the link:

$$tr_x = L_x / V_x \tag{12}$$

where L_x is the length of the link (km); and V_x is the mean velocity of sediment in the link (km/y). There is very little data on sediment velocities or residence times. It can be hypothesised that reaches of high sediment transport capacity will have a high mean sediment velocity. In the absence of comprehensive data on sediment velocity it is reasonable to assume that it is proportional to STC_x:

$$V_x = \frac{1}{k_6} STC_x . \quad (13)$$

Hence:

$$tr_x = \frac{k_6 L_x}{STC_x} \quad (14)$$

where k_6 (t/km) is an empirical constant representing the transient volume of material stored per unit length of river at any time. In an alluvial river it can be considered as the active layer of sediment which is scoured and transported downstream during a flood. For a typical STC_x of 50,000 t/y and V_x of 1000 m/y, k_6 = 50 t/m.

Equation (13) is directly analogous to the constitutive equation for flow, $Q = VA$, where STC is equivalent to Q, and k_6 is equivalent to cross sectional area of sediment once sediment density is included. Specifying a constant assumes that the mass in transient storage is constant and is not itself a function of STC. A similar formulation to Equation (14) is used in Alonso et al. (1981). Equation (14) differs to that used by Pickup et al. (1983) who suggest that the residence time is inversely proportional to $\log_{10}STC$. Both relationships were tested on the Murrumbidgee R., where we have good local knowledge of bed deposition, and 224 of 225 links were found to have the same deposition class from each method so no further testing was pursued and Equation (14) was used in the model. Several values for k_6 were investigated for the Murrumbidgee River. There was little sensitivity to the particular choice but a value of 5 t/m produced results which were both feasible and matched field observations.

The input rate from lateral inputs of bank and gully erosion is constant for years t = 1 to t =100 and the value is given by Equations (4) and (6). Lateral inputs to the link start arriving at the outlet at t = 1 and increase linearly until $t = t_r$ when they reach the lateral input rate. This assumes an even distribution of lateral inputs along a river link. Thus, for bank and gully erosion, the stepped input of Figure 2 is translated into a ramped loading at the link outlet. The total supply of bedload at the outlet (TLC_{xt}) at time t is calculated as:

if $t < tr_x$;

$$TLC_{xt} = (t / tr_x)(IC_x + BC_x);$$

else

$$TLC_{xt} = TC_{x(t-tr)} + IC_x + BC_x \,. \qquad (15)$$

The mass balance at the link outlet is then evaluated for time t. If TLC_{xt} is greater than or equal to STC_x then the sediment yield will equal the sediment transport capacity and the excess sediment will be deposited. Otherwise the yield equals the supply to the outlet and their is no net deposition. Thus sediment yield from the link (Y_{xt}; t/y) is calculated as follows:

if $TLC_{xt} < STC_x$;

$$YC_{xt} = TLC_{xt} \,;$$

else

$$YC_{xt} = STC_x \,. \qquad (16)$$

The total deposition of coarse sediment (TDC_x, tonnes) over 100 y is given by:

$$TDC_x = \sum_{t=1}^{t=100} YC_{xt} - \sum_{t=1}^{t=100} TLC_{xt} \qquad (17)$$

This incorporates both transient and net deposition. Dividing the total deposition by the width of the river bed [Equation (11)], its length (km), and sediment density (ρ = 1.5 t/m^3), gives the mean depth of sediment (DD_x, m) accumulated in the link over the 100 y period:

$$DD_x = \frac{TDC_x}{1500 L_x w_x} \,. \qquad (18)$$

Steady State Budget for Bedload

The transient model can be simplified to a steady state model of average sediment inputs over historical times by removing in the calculations the influence of sediment residence time within a link. This removes all effects of time in the model and the mass balance is solved sequentially downstream through the river network for mean annual inputs, yield and deposition. A period of 100 y was used for the purposes of calculating the total accumulation of sediment on the bed, consistent with the period over which gullies were assumed to have developed. Equations (4) and (6) were used as above to determine the lateral inputs from bank and gully erosion. The mean annual total supply of bedload is given by:

$$TLC_x = BC_x + GC_x + TC_x \qquad (19)$$

and following Equation (1)

$$TC_x = \sum YC_x \ . \qquad (20)$$

The mass balance is than evaluated using the mean annual sediment transport capacity, as described by Equation (9). The total deposition of coarse sediment (TDC_x, tonnes) over 100 y is given by:

$$TDC_x = 100(TIC_x - YC_x) \qquad (21)$$

which is expressed in terms of metres of bed accumulation using Equation (18).

Comparison of Transient and Steady State Bedload Models

Outputs from the two model configurations were compared for the Murrumbidgee R., an area of significant historical bed deposition; and the Burdekin R., where there has been little recorded bed deposition or benthic habitat degradation in historical times. The patterns of deposition produced by the two models were very similar. Over 95% of river links had values within 10% of each other for the two modelling approaches, despite the perceived significance of modelling the long residence times of many river links.

The close match of the two results is produced by the patterns of sediment residence time and their relationship with sediment transport capacity. It was hypothesised that residence time of sediment would be an important factor in river links where the residence time was long compared to that of the history of accelerated sediment transport. In that situation there is a long lag between the stepped increase of erosion and the transmission of the full impact of that step to the link outlet and further downstream. The steady state model only simulates the full impact of the equilibrium load. We believed the transient lag would lead to slower propagation of sand slugs downstream than in the steady state model, with consequent lower deposition at distances far from the source. In reality the lag makes little difference to the results because of its relationship with sediment transport capacity. River links with long residence times have, by definition, low sediment transport capacity. They start depositing sediment well before equilibrium loading is produced, and sediment supply downstream is dictated by the low sediment transport capacity and not the long time to equilibrium. Conversely, river links with high sediment transport capacity, which may not deposit sediment, reach equilibrium loads quickly so again residence time of sediment in the link has little impact on the net response of the link over historical times.

Residence time of sediment in river links is a significant factor on recovery of the river in future from historical deposition if the supply of sediment returns to lower levels (Bartley and Rutherfurd, 1999). This can be easily incorporated into the transient model. Residence time also dictates how quickly the impact develops in the first few years, but again the aim of the model was to examine the total effect of historical erosion on the current sediment condition some 100 to 200 y since it commenced. Similarly, simulating a pulse in sediment supply, rather than a step function of the same total volume, will produce different temporal dynamics of deposition but the same net response over historical times.

We know the total volume of sediment released from gully erosion relatively well from its total extent. We also have some data on total extent of river bank erosion in historical times, but as outlined above there is a high degree of uncertainty in the timing of erosion pulses from gully and bank erosion. There are also no comprehensive data with which to describe the relationship between sediment residence time and sediment transport capacity. Given that the parameterisation of these factors is so uncertain and that their inclusion is unlikely to significantly alter the net response to historical erosion, it was deemed more prudent, parsimonious and rigorous to remove them from the modelling and apply the steady state model to the assessment region of the project.

The bedload model, conceptualised as limited by sediment transport capacity, essentially models the river network as a set of valves of variable size. Upstream increases in supply of sediment to the river network will only be felt downstream if propagation of the increase is not prevented by low sediment transport capacity in any individual link. If a small capacity valve limits downstream yield, then increased supply upstream is absorbed at that point through local deposition. Thus downstream propagation of increased bedload supply is relatively ineffective and is limited by the link of lowest sediment transport capacity along the route to the basin outlet. Increased source erosion will only result in increased delivery to the mouth for paths and sediment sizes that are supply limited. This may explain the ineffective delivery of sand and coarser sediment to the Australian coast and its insensitivity to upstream source changes (e.g. Roy, 1977).

Sediment Budget for Suspended Load

Transient storage since erosion increased in historical times is not significant for suspended sediment. The residence of time of suspended sediment carried within channels is considerably less than the period of increased erosion. The main areas of net accumulation of suspended sediment are floodplains and reservoirs, where sediment residence times are of the order of thousands of years. There is little widespread information available on the temporal dynamics of suspended sediment supply to rivers so a steady state budget was constructed to predict mean annual suspended sediment loads. This level of information is adequate for regional planning of land use change and catchment restoration and for identifying the spatial patterns of sediment sources, yields and potential impacts.

The suspended sediment loads of Australian rivers, and rivers in general, is supply limited (Olive and Walker, 1982; Williams, 1989). That is, rivers have a very high capacity to transport suspended sediment and sediment yields are limited by the amount of sediment delivered to the streams. Consequently, if sediment delivery increases, sediment yields will increase proportionally. Deposition is still a significant process, however. This can be illustrated by plots of suspended sediment yield data against catchment area (Figure 3). These plots show a reduction in sediment yield per unit area with increasing catchment area. Such a decrease in specific sediment yield is not satisfactorily explained by decreases in erosion intensity in large catchments (Richards, 1993). The more likely explanation is deposition of sediment within river systems, and the most significant depositional areas are floodplains and reservoirs. Hence this, and description of the sediment sources form the basis for the suspended sediment budget, aimed at predicting regional patterns of sediment loads.

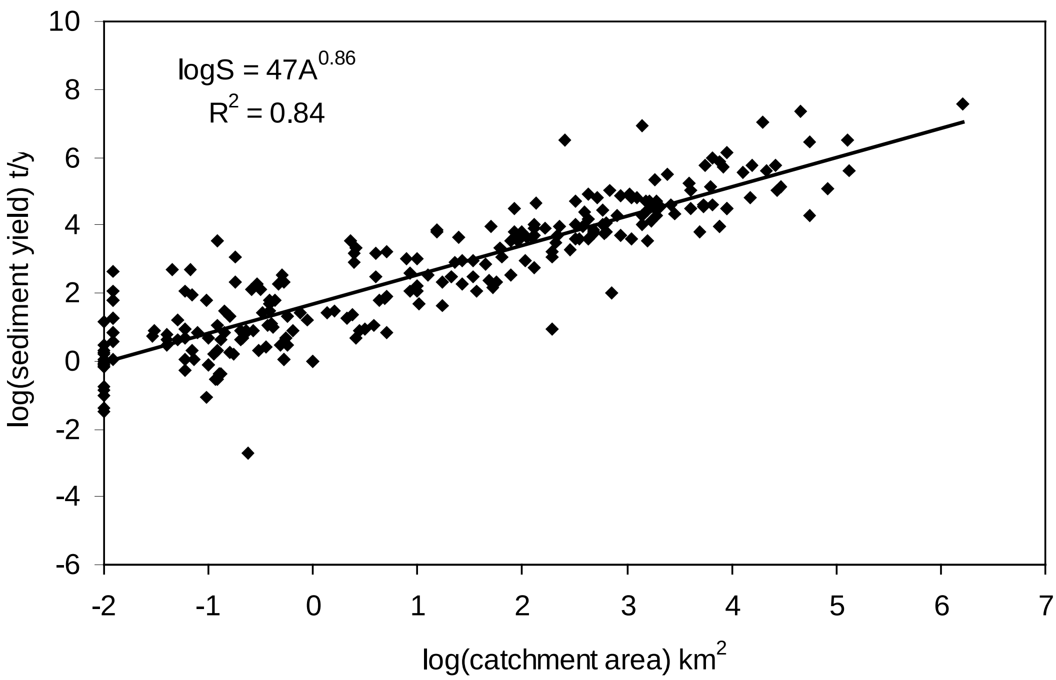

Figure 3. Sediment yield data for Australian catchments compiled by Wasson (1994). Only data for areas >0.01 km^2 are shown.

Suspended sediment is supplied to a river link from four sources: river bank erosion, gully erosion, hillslope erosion and tributary suspended sediment yield. The supply of sediment from tributary sediment yield, and river bank, and gully erosion is described above in Equations (1), (4) and (6). For suspended sediment supply (TFS_x, t/y) the symbol F is used instead of C, and for gully (GF_x, t/y) and riverbank erosion (BF_x, t/y) the proportion of total load that contributes to suspended load is used (1 – PC). A value of 0.5 was used for PC, providing an equal contribution to bedload and suspended load. Thus:

$$TIF_x = TF_x + GF_x + BF_x + HF_x \qquad (22)$$

Sediment supply from sheetwash and rill erosion on hillslopes was determined from a 9" resolution grid of USLE soil erosion predictions described in Lu et al., (2001). Only a small proportion of sediment moving on hillslopes is delivered to streams. The difference occurs for two reasons. First the USLE is calibrated against hillslope plots considerably smaller than the scale of hillslopes. Much of the sediment recorded in the trough of the plots may only travel a short distance (less than the plot length and much less than the hillslope length) so that plot results cannot be easily scaled up to hillslope predictions. Second there are features of hillslopes, not represented by erosion plots, which may trap a large proportion of sediment. These include farm dams, contour banks, depressions, fences, and riparian zones. The most common way of representing the difference between plot and hillslope sediment yields is to apply a hillslope sediment delivery ratio (*SDR*) to the USLE results (e.g. Williams, 1977; Van Dijk and Kwaad, 1998). The total mean annual supply of hillslope erosion to streams in the internal catchment of each link is then:

$$HF_x = SDR \sum_{j=1}^{j=n} A_j \qquad (23)$$

where A_j is the mean annual soil erosion rate predicted by USLE for each cell j in an internal catchment containing n cells.

The suspended sediment budget is evaluated at the outlet of each river link, working progressively from the top of the river basin to its mouth. A relatively simple conceptualisation of floodplain deposition is to consider that the proportion of suspended sediment load that is available for deposition is equal to the fraction of total discharge that goes overbank. This assumes uniform concentration of suspended sediment with depth. The actual deposition of material that goes overbank can be predicted as a function of the residence time of water on floodplain, acknowledging that floodplain water can return to the river before sediment has settled out. If we assume that only deposition and not re-entrainment of sediment occurs, then the proportion of sediment leaving the floodplain to that entering the floodplain is (Dabney *et al.* 1995):

$$\frac{C_o}{C_i} = e^{-\left(v/q \right) x} \qquad (24)$$

where C_o is the output sediment concentration, C_i is the input concentration of particles of a given size, v is the settling velocity of particles, q is the discharge per unit width (Q/w) and x is the distance travelled over the floodplain. The outgoing sediment concentration can be expressed as a ratio of sediment yield to discharge; and the incoming concentration as supplied sediment to discharge. The mean annual suspended sediment yield (YF_x) from each link is merely:

$$YF_x = TIF_x - D_x \, . \qquad (25)$$

Combining Equations (24) and (25) produces the total deposition (D_x, t) on the floodplain:

$$D_x = \frac{Q_f}{Q} \left(TIF_x \right) \left(1 - e^{-\left(\frac{vA_f}{Q_f} \right)} \right) \qquad (26)$$

where A_f is floodplain area ($A_f = wx$) and Q_f is floodplain discharge ($Q_f = Q - Q_b$ where Q_b is bankfull discharge). Equation (26) needs to be integrated across the frequency spectrum of significant sediment transporting events, as described below, to express the deposition as a man annual value (t/y). Dividing D_x by the floodplain area expresses deposition as the mean annual rate of floodplain aggradation. Mapping of floodplain area for each river link is described in Pickup and Marks (2001).

An increase in supply of fine sediment from upstream result in a concomitant increase in mean sediment concentration and mean annual suspended sediment yield. Thus increases in fine sediment supply have relatively strong downstream influences on suspended sediment loads.

Reservoir Deposition

Sediment deposition in reservoirs is incorporated in the model in addition to the algorithms for bedload and floodplain deposition along rivers. There are over 430 large dams on Australia's rivers (Anon., 1990). These structures greatly effect sediment delivery through the long residence times of water in the dams and the obstruction that the dam wall makes to bedload. Only dams with a height of greater of than 10 m and an impoundment large enough to be mapped on the 125,000 topographic map series were incorporated in the model. Bedload transport was prevented from passing through the mapped dams. Most dams are also efficient stores of suspended sediment. The sediment trap efficiency (proportion of supplied load that is trapped) was calculated by an update (Heinemann, 1981) of the empirical Brune rule (Brune, 1953) which expresses sediment trap efficiency (*TE*, %) as a function of the storage volume of the reservoir (*C*, Ml) and the mean annual input discharge (*I*, ML):

$$TE = -22.0 + \frac{119.6\, C/I}{0.012 + 1.02\, C/I} \qquad (27)$$

This is a residence time approach similar in form to that applied for floodplain deposition.

Contribution of Sediment to the Coast

One of the strongest interests in suspended sediment transport at present is the potential downstream impacts on receiving water bodies. These may include high value river reaches, lakes and reservoirs, but the ultimate point of delivery and one of particular concern is delivery to estuaries and the coast. There is particular concern over sediment delivery to estuaries such as Moreton Bay (Tibbetts et al., 1998) and to the Great Barrier Reef Lagoon. Because of the extensive opportunities for floodplain deposition along the way, not all suspended sediment delivered to rivers is transported to the coast. There will be strong spatial patterns in sediment delivery to the coast because some tributaries are confined in narrow valleys with little opportunity for deposition, while others may have extensive open floodplains. There will also be strong, but different patterns in sediment delivery to streams. Differentiation of subcatchments which contribute strongly to coastal sediment loads is important because of the the very large catchments involved in Australia; the Burdekin River drains an area of 130,000 km^2 for example. It is not possible, or sensible, to implement erosion control works effectively across such large areas.

Once suspended sediment inputs and yields were predicted for each river basin using the methods outlined above we used the information to calculate the contribution of each link subcatchment *x* to the mean annual suspended sediment yield from the mouth of the basin (CO_x; t/ha/y). The calculation takes a probabilistic approach to sediment delivery through each river link encountered on the route from source to catchment mouth. Each internal link catchment area delivers a mean annual load of suspended sediment (LF_x) to the river network. This is the sum of gully [Equation (6)], hillslope [Equation (23)] and bank erosion derived sediment [Equation (4)]. This contributes to the total load of suspended sediment [TIF_x; Equation 22] received by each river link. Each link yields some fraction of that load (YF_x). The ratio of YF_x/TIF_x is the proportion of suspended sediment that passes through each link. It can also be viewed as the probability of any individual grain of suspended sediment passing through the link. The suspended load delivered from each subcatchment will pass through a number of links on route to the catchment mouth. The amount delivered to the mouth is the product of the loading LF_x and the probability of passing through each river link on the way. Dividing this by the internal catchment area expresses CO_x as an erosion rate (t/ha/y):

$$CO_x = LF_x \, x \, \frac{YF_x}{TIF_x} \, x \, \frac{YF_{x+1}}{TIF_{x+1}} \, x......x \, \frac{YF_n}{TIF_n} \qquad (28)$$

where n is the number of links on the route to the outlet. The proportion of suspended sediment passing through each river link is ≤ 1, thus a consequence of Equation (28) is that all factors being equal the further a sub-catchment is from the mouth the lower the probability of sediment reaching the mouth. This behaviour is modified though by differences in source erosion rate and deposition intensity between links.

Suspended Sediment Budget Under Natural Conditions

There are naturally strong differences in suspended sediment load across the diverse environments of Australia. To assess the extent to which the current sediment loads reflect the natural circumstances, and to what extent they reflect accelerated sediment supply, requires prediction of natural sediment loads. This is necessarily a fairly speculative process as there is limited knowledge of natural conditions, and no sediment load data other than for a few small catchments which remain relatively undisturbed. The natural rate of hillslope erosion was estimated by interpolating the predicted rate under current conditions in reserves of native vegetation to cleared lands (Lu et al., 2001). The delivery of this sediment to streams was calculated using Equation (23), assuming an unchanged hillslope sediment delivery ratio to present. The natural rate of gully and riverbank erosion are negligible compared to current rates and were not included in the analysis, thus all sediment is supplied from hillslopes. Deposition was modelled by Equation (26), as for current conditions, and reservoir deposition was omitted.

Hydrology

Several hydrological parameters are described in the sediment budget methods. These need to be predicted for each river link across the assessment area. The variables needed are:

1. the mean annual flow
2. the mean annual sum of $Q^{1.4}$ for calculating mean annual sediment transport capacity;
3. the bankfull discharge; and
4. a representative flood discharge form floodplain deposition.

Values for mean annual flow were derived from available gauging records and a simple empirical rule based upon rainfall and catchment area was used to predict values in ungauged river links. The other three hydrological parameters were derived also derived from gauging records by regression against mean annual flow.

Mean Annual Flow

Mean annual flow data were obtained from Peel *et al*. (2000), who extended the daily record of 282 gauging stations to cover a period of 100 y. Modelled daily flow was based upon a conceptual rainfall to runoff model calibrated against the recorded flow. Records of daily catchment rainfall were used to extend the gauging data to cover the period 1900 to 1999. The modelled data has the advantage of removing differences in runoff between gauging stations that result from variable monitoring periods superimposed upon decadal scale variability in annual rainfall and runoff. The modelled data was supplemented by historic daily flow records for 35 unregulated Queensland gauge stations.

The records of mean annual flow (*MAF*) were related to upstream catchment area (*A*) and spatially-averaged upstream mean annual rainfall (*R*) by multiple linear regression of the form:

$$\log_{10} MAF = k + m\log_{10} A + n\log_{10} R \qquad (29)$$

Mean annual rainfall was calculated from grids of daily rainfall data provided by the Queensland Department of Natural Resources (see QDNR 2000). The spatial resolution of the daily rainfall grids is 5 km based on interpolation of over 6000 rainfall stations in Australia.

Using all 317 data points in the regression m = 0.928 and n = 2.386 (R^2=0.87).

There were large regional difference in runoff generation, so the coefficient *k* in Equation (29) was fitted to three regional subsets of the data. The three regions were defined by homogeneity of annual runoff coefficients defined as *MAF/(AR)* with resultant values for *k*:

1. Region 1: Drainage Divisions 1, 2, 4 (Basins 1 to 15), 6, 7, 8, 9; mean annual runoff coefficient of 0.21; *k* = -4.790, 261 data points, adjusted R^2 = 0.86
2. Region 2: Drainage Division 3; mean annual runoff coefficient of 0.41; *k* = -4.413, 12 data points, adjusted R^2 = 0.82
3. Region 3: Drainage Divisions 4 (Basins 16 to 26) and 5; mean annual runoff coefficient of 0.09; *k* = -4.834, 43 data points, adjusted R^2 = 0.85

The three regionalised regression equations were used to predict mean annual flow in each river link of the assessment area. Graphs of predicted mean annual flow against observed values are shown below, with linear regression equations.

Sediment Transport Capacity

To calculate the mean annual sediment transport capacity within each river link requires information on the mean annual sum of daily flow values raised to the power of 1.4 and capped to the bankfull discharge [abbreviated to $\Sigma Q^{1.4}$; see Equation (9)].

Values for $\Sigma Q^{1.4}$ were obtained for 409 gauging records including the modelled data of Peel *et al.* (2000), other modelled natural data (mostly from inland NSW catchments), observed data from unregulated large catchments, and observed pre-regulation data from large regulated catchments. These were regressed against the observed mean annual flows for the stations producing the model (Figure 4):

$$Log_{10} \Sigma Q = 1.3569 Log_{10} MAF - 0.649 \qquad (30)$$

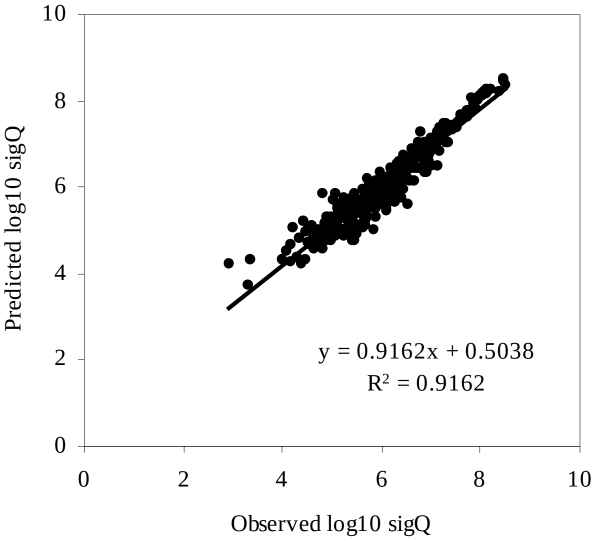

Figure 4. Predicted vs observed $log_{10}\ \Sigma Q$. Slope of predicted:observed line=0.92, average ratio of predicted:observed=1.25.

Bankfull Discharge

Bankfull discharge is used in the model to predict the rate of bank erosion, and separate flood flows from in-channel flows. Early studies found Q_b had a recurrence interval of between 1 and 2 y (Wolman and Leopold 1957) and there is widespread use of the mean annual flood as Q_b (Dury *et al.* 1963) on stable rivers. The mean annual flood has a recurrence interval of 1.58 y. More recent reviews of data found Q_b could be much higher (Williams 1978). Many Australian rivers have a history of channel incision and widening that have increased bankfull discharge markedly (Brooks 1999) and strong departures of Q_b from the mean annual flood have been observed (Pickup and Warner 1976; Nanson and Young 1981; Nanson 1986). As yet though, no methods have been developed to define the variability in bankfull discharge within in a river system, let alone between river systems. Consequently we conformed to the almost universal practise of defining the bankfull discharge as the 1.58 year recurrence interval event.

The model for bankfull discharge ($Q_{1.58}$, Ml/day) is based on the 409 points described above, regressed against observed mean annual flow to produce the model (Figure 5):

$$Log_{10} Q_{1.58} = 0.8888 Log_{10} MAF - 0.8891 . \qquad (31)$$

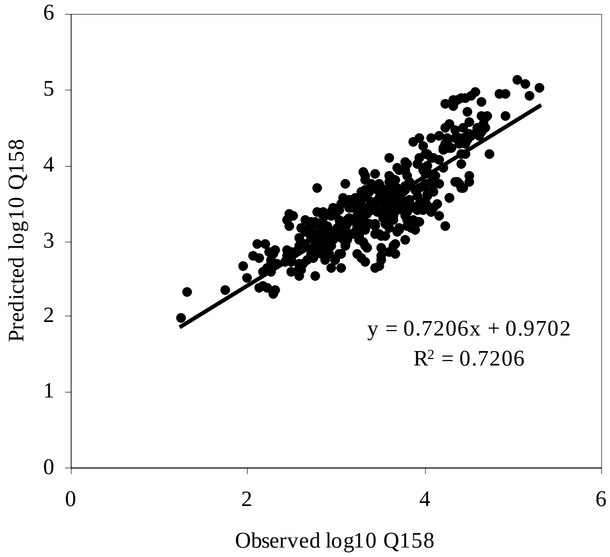

Figure 5. Predicted log_{10} $Q_{1.58}$ vs observed log_{10} $Q_{1.58}$. Slope of predicted:observed=0.72, and average ratio of predicted:observed=1.4.

Median Overbank Discharge

To predict mean annual floodplain deposition requires a value for a typical overbank discharge used to represent the mean annual rate of floodplain deposition. There is an exponential relationship between deposition and overbank flow (Equation 26). It was found that the median flow in excess of bankfull was representative of the mean deposition produced by the frequency distribution of events transformed by the exponential relationship. The model for median overbank discharge (*QOB*; Ml/day) is based on 405 points, as a few data sets were too small to reliably determine a median values for flows greater than $Q_{1.58}$. The model produced is (Figure 6):

$$Log_{10}QOB = 0.9139Log_{10}MAF - 0.7787 . \qquad (32)$$

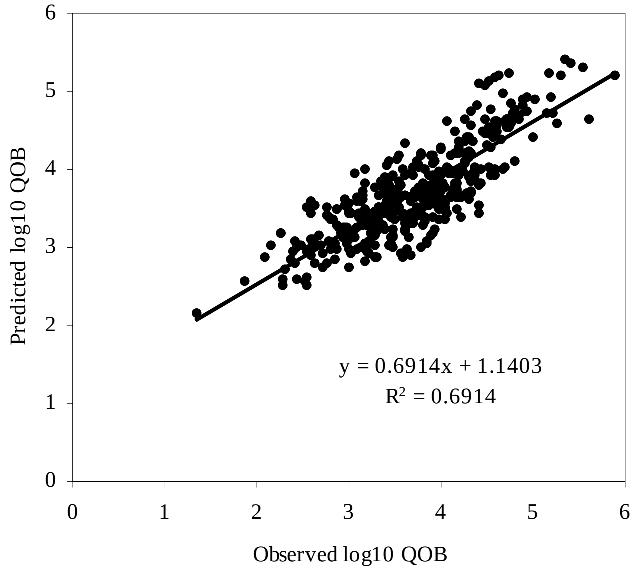

Figure 6: Predicted log_{10} *QOB* vs observed log_{10} *QOB*. Slope of predicted:observed=0.69, and average ratio of predicted:observed=1.5.

Model Implementation and Validation

Most parameters required for the model have been set by empirical relationships against extensive data sets, for example hydrology, river width, and bank erosion. There are, however, three model parameters that have not been set in the discussion above. These are the sediment delivery ratio from hillslopes [Equation (23)], sediment settling velocity for bedload [Equation (9)] and sediment settling velocity for floodplain deposition. These three parameters can all be interpreted in terms of the physical processes of sediment transport and field observations. There are, however, no data sets to show spatial patterns of the variables. They were set as global constants across the assessment area, with the exception of hillslope sediment delivery ratio for which the assessment area was split into two geographic regions as explained below.

The aim of the bedload sediment budget was to predict the extent of sand slugs derived from massive increases in supply of sand and gravel to rivers from gully erosion and accelerated bank erosion. Observations of the sand slug deposits show that they are composed of coarse sand and fine gravel (Rutherfurd, 1996) so a mean particle size of 2 mm was used in Equation (9) to determine sediment transport capacity. Conversion of particle size to sediment settling velocity followed the procedures described by Richards (1982; p. 77-79). Other values were tested to examine the sensitivity of the choice made. It was found that an order of magnitude change in particle size was required to significantly alter patterns of deposition in river networks. Predictions based upon finer particle sizes resulted in the focus of deposition being pushed further downstream to reaches of very low sediment transport capacity. The opposite occurred using a coarser mean particle size. As well as matching field observations, the mean particle size used produced patterns of deposition similar to those mapped in the Glenelg Rivers, and conforming with our own field knowledge of the Murrumbidgee R.. No comprehensive mapping of sand slugs has been published in Australia outside of the Glenelg R. catchment (Rutherfurd, 1999) and further testing of the bedload model across diverse rivers is needed.

The sediment delivery ratio from hillslopes and the particle settling velocity for floodplain deposition influence patterns of suspended sediment supply to rivers, suspended sediment yields and deposition. Changes to the sediment delivery ratio change the total mass of sediment supplied to rivers and the mean annual loads and mean annual deposition rate of each river link rise proportionally. Changes to the sediment settling velocity influence the intensity of deposition through the river network. An increase in settling velocity increases the proportion of suspended load that is deposited on floodplains and decreases the sediment yield from the basin. In terms of the traditional plot of suspended sediment yield (*log S*) against catchment area (*log A*; Figure 3), reducing the hillslope sediment delivery ratio maintains the pattern of values but lowers all values on the plot. Reducing the sediment settling velocity increases the gradient of the regression line through the points and thus increase the sediment yield from the river basin. Changing the hillslope sediment delivery ratio also changes the ratio of sediment supplied from hillslopes to that supplied from channel processes (gully and bank erosion).

Five criteria were used to evaluate appropriate values for hillslope sediment delivery ratio and sediment settling velocity. These were:

1. calibration against observed suspended sediment loads of rivers;
2. shape of regressions of *log S* against *log A*;
3. mean annual rate of floodplain deposition;
4. mean annual rate of reservoir infilling; and
5. ratio of hillslope to channel sediment sources.

Measurements of mean annual suspended sediment loads are scarce in Australia but some data is available to calibrate the model and evaluate the bounds of suspended sediment yield. For this project we focussed on getting a good geographic spread of river load data, and focussed on larger catchments where errors might become more apparent as the sediment budget is essentially built from the bottom up by summing all the source terms, allowing for losses along the way.

Wasson (1994) has produced regional plots of *log S* against *log A* for Australia using data available at the time. The data span a huge range in scales from 10^{-6} to 10^{6} km^2, and linear regression of the form:

$$\log S = a \log A + b \qquad (33)$$

was fitted to the data. Only the data above 50 km2 is relevant for comparison against the river model results. A feature of the data is the common observation that the value of *a* is usually less than 1, but generally greater than 0.8, implying storage of sediment as catchment scale grows (Walling, 1983). The best regional relationship is for the southern uplands of Australia where the exponent = 0.94 (Wasson, 1994), but even there the uncertainty on that value is high when only river scale data is considered.

The mean annual rate of deposition on floodplains is predicted by Equation (26). It is conceivable that the suspended sediment model could predict the correct catchment sediment yields by using a gross over estimate of sediment supply and absorbing the error in floodplain deposition. This could occur by not applying a hillslope sediment delivery ratio for example. Such an error would result in high values of floodplain deposition. Floodplains accumulate sediment at rates of the order of 1 - 2 mm/y or less, producing 1 - 2 m of aggradation in 1000 y (eg. Walling et al., 1992), and constraining model parameterisation.

A similar argument can be made for reservoir deposition. Large reservoirs are effective sediment traps, usually trapping >90% of incoming sediment load (Outhet, 1991), but if the predicted loadings to reservoirs are overestimated then they will be predicted to fill with sediment within several decades. Observations of sediment deposits in Australian reservoirs suggest that they will be viable for centuries to thousands of years under current accumulation rates (Davis et al., 1997).

Radionuclides from atmospheric fallout have been used to partition suspended sediment in rivers between surface derived materials, relatively rich in attached radionuclides from sub-surface derived materials relatively deficient of radionuclides (Wallbrink and Murray, 1993). The most obvious surface sources of sediment are sheetwash and rill erosion of hillslopes. Gully and riverbank erosion supply predominantly sub-surface material. Several catchments in SE Australia have sediments dominated by sub-surface radionuclide signatures (values up to 95%) suggesting that gully and bank erosion are the primary sediment sources (Olley et al., 1993; Wallbrink et al., 1998; Prosser et al., 2001).

The best match against the criteria given above was to use a sediment settling velocity of 1 x 10^{-6} m/s across the assessment area and a hillslope sediment delivery ratio of 0.05 or 0.1 depending upon region. A sediment delivery ratio of 0.1 was used for the Burdekin, Fitzroy and north Queensland regions, and a value of 0.05 was used elsewhere. The settling velocity is equivalent to particles of 0.033 mm diameter, which is in the silt range and well within the bounds of materials found on floodplains. The higher value for sediment delivery ratio in Queensland was needed to produce the observed sediment yields from the Johnstone, Burdekin, and Fitzroy Rivers. A higher delivery ratio for those areas may is feasible given the intense long duration tropical storms which enhance sediment transport on hillslopes. A plot of observed and predicted river sediment yields is shown in Figure 7. The match is very good considering the limited parameterisation and vast geographical spread of the predictions. Figure 7 does not just represent catchment size, as there are strong differences in area specific sediment yield between the catchments shown.

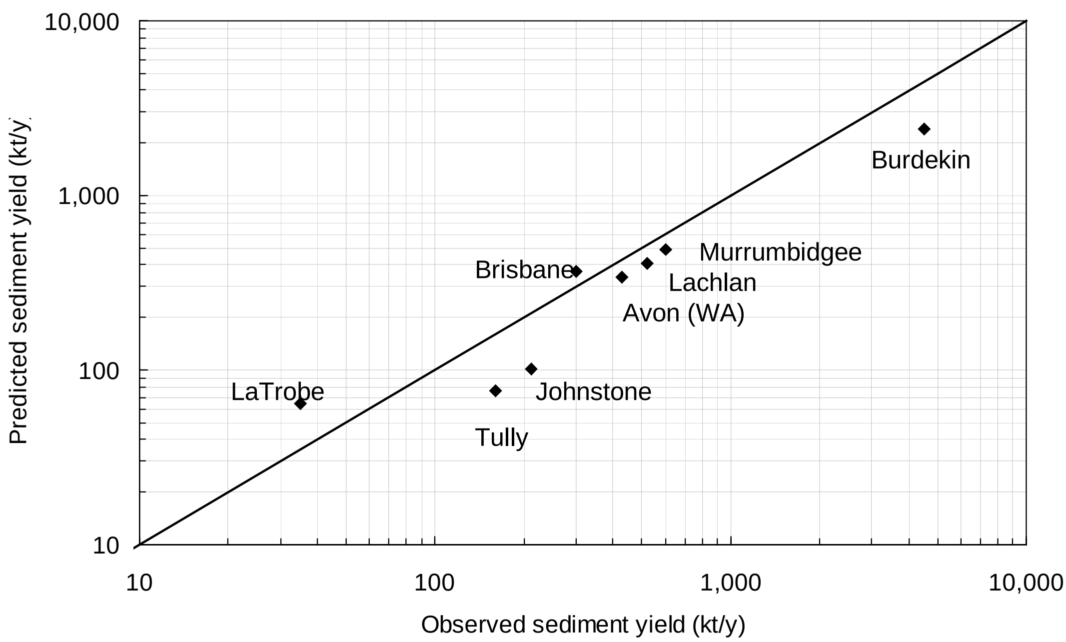

Figure 7. Observed versus predicted sediment loads for rivers spread across the assessment area.

Applying a sediment settling velocity of 1 x10^{-6} across the assessment area produced a value of *a* from the model of 1.05 to 0.79. For the southern uplands, where monitoring data is best the predicted value of *a* is 0.87 compared to that of *a* = 0.94 from Wasson (1994). These values are very close given the order of magnitude range of sediment yield in both measurement and prediction for any given area. Over 90 % of river links were predicted to have floodplain deposition of less than 2 mm/y and 98% had less than 3 mm/y of deposition. Over 99 % of the large dams were predicted to have capacities to store greater than 100 y of sediment. Without the application of a low sediment delivery ratio, hillslopes dominate the supply of sediment to streams. Applying a value of 0.05 to south eastern Australia resulted in >80% of sediment being delivered from gully and riverbank erosion, close to the independent estimates from radionuclide analysis. Other features of the model which suggest that the results produce realistic values include that by the mouth of catchments suspended sediment makes up approximately 90% of the load despite gully and bank erosion contributing evenly to bedload and suspended load.

Sand slugs have been mapped in the Glenelg R. (Rutherfurd, 1996). The model predicts this to be one the most impacted rivers for bedload, as found in the field. The coarseness of the river network and sediment supply terms in the model means that it will not predict the detailed distribution of slugs in the catchment (calculations are averaged over a link for example). The broad location and extent of impacted reaches is relatively well predicted however (Figure 8).

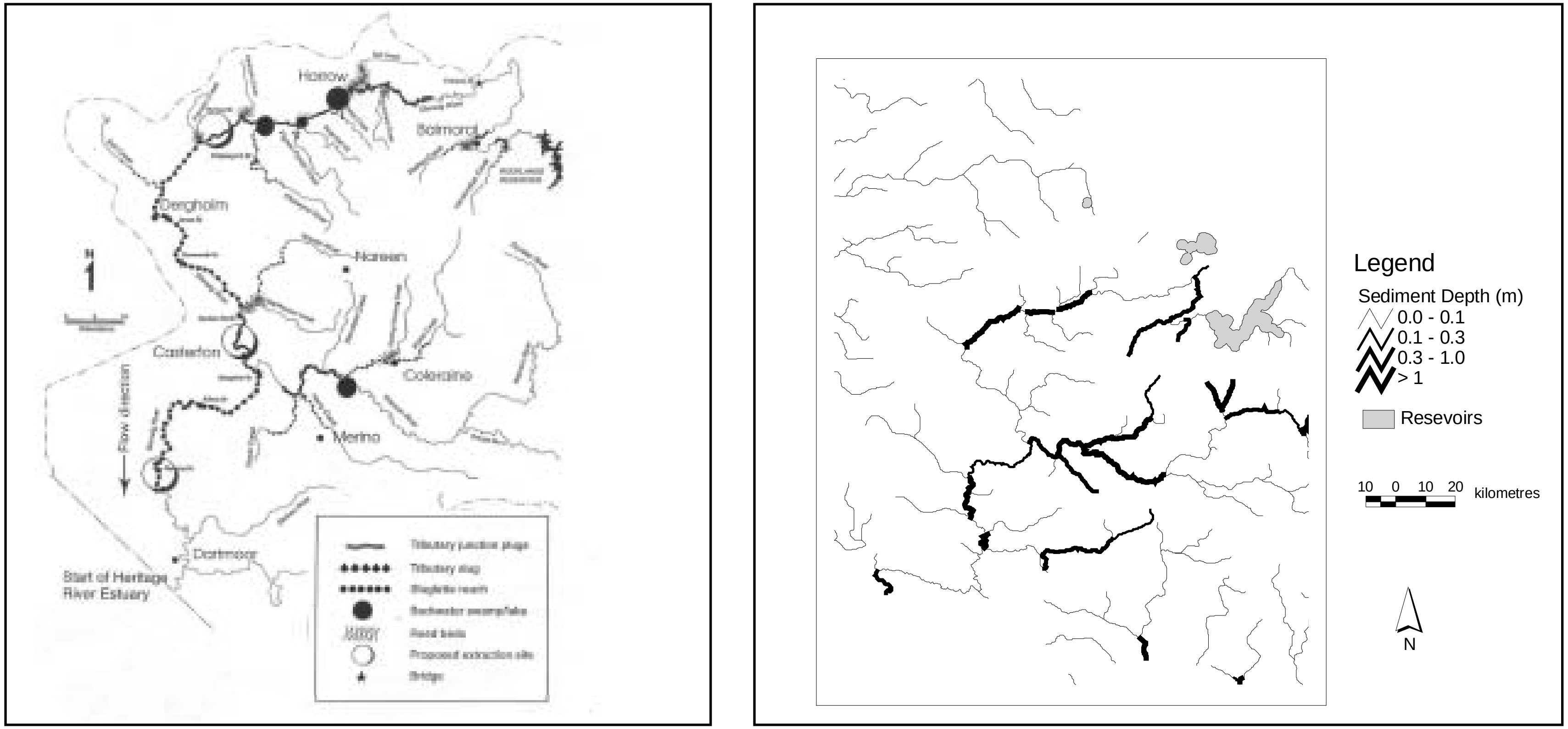

Figure 8. Observed versus predicted locations of sand slugs in the Glenelg R. catchment of W. Victoria. Observed map reproduced from Rutherfurd (1999).

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